LIGHTING RESEARCH PROGRAM

Project 3.3 California Classroom Simulation Report
FINAL REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

CONSULTANT REPORT

Arnold Schwarzenegger, *Governor*

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CALIFORNIA ENERGY COMMISSION

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California Energy Commission
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Simulation Analysis Report
Final Report

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Executive Summary

This study addresses a number of different important issues related to photosensor system performance. Performance parameters such as photosensor spatial distribution, location within a space were studied by comparing the relative agreement between the photosensor's signal and the work plane illuminance at a critical point within the space. As in previous studies, the photosensor's view of the window was an important parameter. Photosensors that are influenced less by direct light coming from the window due to a narrower spatial sensitivity or due to a mounting position farther from the window or daylight aperture generally show better agreement with the daylight illuminance at the targeted point.

In addition, the impact of changes in localized work plane reflectance on photosensor performance was studied. Sensors with a wider view of the space are impacted less by these changes, was would be expected.

An ideal location for a sensor is on the ceiling within a space, but with indirect lighting systems, the photosensor must not receive a strong signal from the electric lighting system that it is controlling. For this reason, it is best to position the sensor midway between two rows of luminaires and provide it with sufficient cutoff in it spatial distribution such that the impact on the photosensor's signal from direct light is minimized. A compromise between a wide signal to minimize work plane reflectance variations and a limited width to minimize the impacts from indirect lighting is a spatial distribution with a 55-degree half angle. This sensor still provides some latitude with regard to placement between two rows of indirect luminaires.

A number of photosensor calibration and related performance issues were also addressed. In spaces where direct sunlight is allowed to penetrate into the space, these conditions will generally provide the highest photosensor signal to work plane illuminance ratio. If the photosensor system is calibrated at daylight conditions that provide no direct sunlight, the presence of direct sunlight in a space will likely result in over-dimming of the electric lighting equipment. Excluding these direct sunlight conditions, calibration should occur under conditions that maximize the photosensor signal to work plane illuminance ratio. This condition is generally one where horizontal blinds are applied, and the blinds are angled to permit the photosensor to have a view of the exterior, while the work plane's view of the sky is blocked by the blinds.

Graphs of the daylight distribution and energy performance of photosensor systems in classroom spaces with from three rows of luminaires show that savings can generally be maximized in spaces with unilateral sidelighting when the two rows closest to the window are dimmed. In spaces with bilateral daylighting, energy use is generally minimized when the entire lighting system is dimmed. This analysis only considered one dimmed lighting zone, but estimated the energy consumed over a typical year if one, two and three rows respectively were assigned to this dimmed zone. Energy consumption in the unilateral case was in the range of 60% of that provided by no dimming whereas it was approximately 35-55% under the bilateral conditions when the entire room was dimmed. The lightshelf condition that was studied provided much lower daylight illumiance levels and energy savings than the other lighting system that were considered.

The analyses that were performed for this study focused primarily on the ability of the photosensor to accurately track the level of daylight in a space. Lighting quality issues on special task areas such as chalkboards were not addressed, but these must be considered in the layout of a lighting design in a classroom space.

Introduction

This project involves a detailed analysis of photosensor system performance in a variety of classroom spaces to gather important information that will be applied to the design of a new photosensor system for application in schools. Detailed computer modeling was performed for six selected classroom spaces. These classrooms were selected to represent designs that have been applied in the state of California, and each introduces daylight into a classroom space using a different single or combination of delivery systems.

The original project proposal indicated that five spaces would be considered, however after the computer modeling had begun, we identified a sixth space, a modular classroom unit that had some rather unique properties, and added it to the list as Classroom 6.

To fully study photosensor performance in these classrooms, a task that addresses the correlation between the photosensor signal and the work plane illuminance, a number of smaller studies that impact photosensor performance were also conducted. One involves the impact of indirect lighting on a ceiling-mounted photosensor. A second involves the impact of changes in work plane reflectance on the photosensor signal. A third involves the energy savings that might be achieved with different arrangements of the dimmed lighting zone.

The design of a new photosensor system requires that a number of different and important issues be addressed simultaneously. The work presented here provides important details that will help to guide decisions with respect to the design of the new photosensor system, including its spatial distribution, control algorithm, recommendations for sensor location and calibration procedures to use in its application.

Background

In this project, the significance of a photosensor's spatial response, placement and the impact of different sky, blind and electric lighting conditions are addressed in detail. Prior studies have shown that daylight and blind conditions can create problems if a system is incorrectly designed or applied. The goal in the design of any photosensor control system is to create a system where the photosensor signal and the work plane illuminance are highly correlated – typically with a linear relationship. That is, if the work plane illuminance due to daylight doubles, so does the photosensor signal due to daylight. In daylight situations with image preserving vertical glazing, this does not always occur. The reason is that the distribution of daylight entering a space through a window can be affected significantly by different sky and blind conditions. The following paragraphs will explain some of the problems that we hope to eliminate or minimize in the photosensor system being designed.

Let's first consider the photosensor signal to work plane illuminance ratio and the condition presented by an overcast sky. An overcast sky is one where direct sunlight is completely obstructed and a continuous layer of clouds eliminates the view of the sky. The luminance at zenith (straight up) is generally about 2½ times the luminance at the horizon in the standard overcast sky models. Because there is no direct sunlight, the horizontal illuminance on the ground is rather low, and because the ground generally has a low reflectance, little light is reflected from the ground. For a clear window and an overcast sky, there is much more daylight passing through window in a downward direction than in an upward direction (see the overcast sky schematic in Figure 1).

Now let's consider a clear sky condition. When looking away from the sun, the sky might not be any brighter than our overcast sky, but the sunlight striking the ground will make the ground much higher in luminance in comparison to what is present under an overcast sky condition. Under clear sky conditions, with a clear window (i.e., image preserving glass), there is much more daylight passing through the window in an upward direction, while the amount of daylight coming from the sky might be relatively unchanged, or even slightly lower, than in the overcast condition (See Figure 2). If a photosensor on the ceiling of a space has a view of the window, the signal that it receives can be significantly higher than in the overcast sky condition. However, the amount of daylight reaching the work plane does not increase by the same relative magnitude, because the daylight striking the ceiling is reflected diffusely in all directions. These two sky conditions (clear and overcast) present very different signal to work plane illuminance ratios. If the sensor signal to work plane illuminance is to follow a linear relationship, the sensor cannot receive direct light from the window. Other sky and blind conditions present similar problems, as discussed below.

Let's now consider a window with horizontal blinds. If the blinds are oriented horizontally (not tilted), we have a relatively unobstructed view through the blinds if we look horizontally at the window. However, both the sensor's view of the ground and the work plane's view of the sky will be somewhat obstructed by the blinds. Depending on the exterior daylight condition, the relative luminance of the top and bottom of the blinds, which direct light to either the photosensor or work plane, respectively, can be different. For an overcast sky condition, the top of the blinds is likely to be brighter. Logically then, for a north-facing clear sky condition, light reflected from the ground will strongly impact the luminance of the underside of the blinds. Because of interreflection that occurs between the upper and lower surfaces of the blinds, the resulting differences in the sensor to work plane illuminance ratio is not likely to be as great as in the no-blind condition, but it still could increase the sensor signal to work plane illuminance ratio.

Let's look at a few other conditions. If we consider a south-facing window with direct sunlight striking the blinds, the top of the blinds is likely to be extremely bright. If the photosensor has a view of the window, the sensor signal is likely to be much higher, resulting in an increased photosensor signal to work plane illuminance ratio (Figure 3). Now, what if the blinds are angled to block the direct sunlight? How does this impact the photosensor signal to work plane illuminance ratio? A point on the work plane will see the backside of the blinds, and its view of the bright sky will be eliminated. Meanwhile, the photosensor may have a view through the blinds of a bright sunlit ground. The result is a high photosensor signal with a potentially lower work plane illuminance. These conditions are also illustrated in Figure 3.

How can we eliminate this variation in photosensor signal to work plane illuminance ratio that makes it difficult to accurately dim an electric lighting system based on the photosensor signal received? The variations in this ratio appear to be caused in large part by the photosensor's direct view of the window. This view can be reduced by locating the photosensor deeper into the space, or by restricting the photosensor's view of the window by narrowing its field of view (See

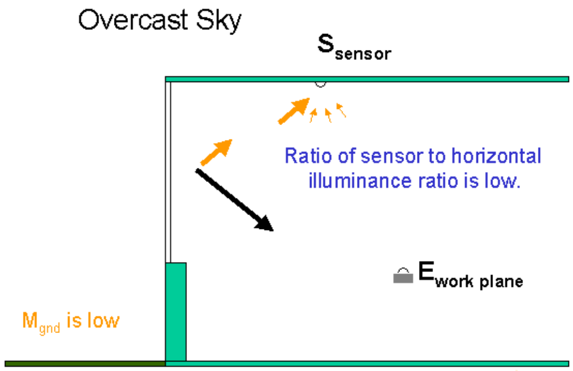


Figure 1. The relative magnitude of light passing through transparent glazing in a downward and upward direction from an overcast sky produces a low photosensor signal to work plane illuminance ratio.

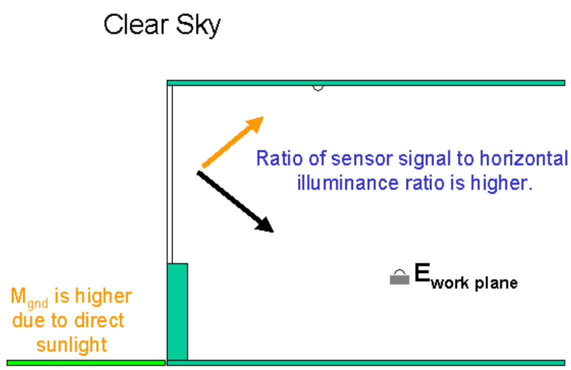


Figure 2. The relative magnitude of light passing through transparent glazing in a downward and upward direction from a clear sky with sunlit ground would produce a relatively high photosensor signal to work plane illuminance ratio.

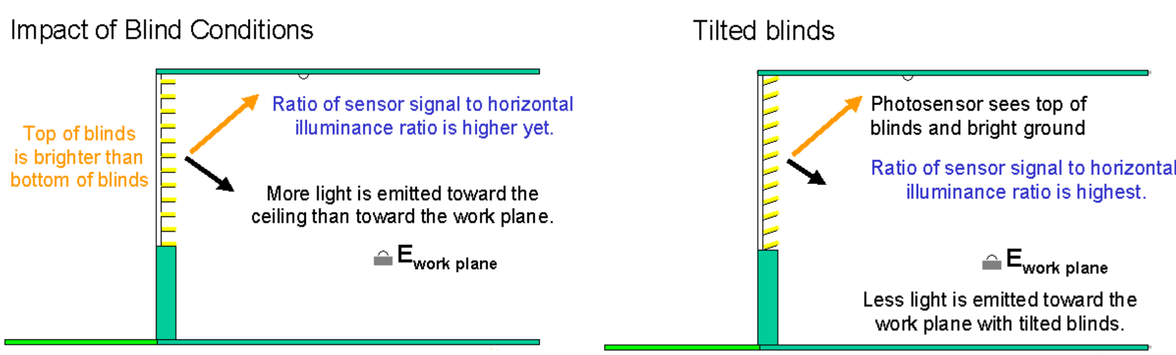


Figure 3. Blinds, when illuminated with direct sunlight, will produce a relatively high photosensor signal to work plane illuminance ratio.

Figure 4). This study will investigate different photosensor spatial sensitivity distributions as well as difference photosensor locations for a variety of different glazing and daylight delivery system configurations. While prior research studies have generally considered photosensors in a single space, this study will address a variety of different daylit spaces to identify a photosensor system that will work effectively across a wide variety of different daylight conditions.

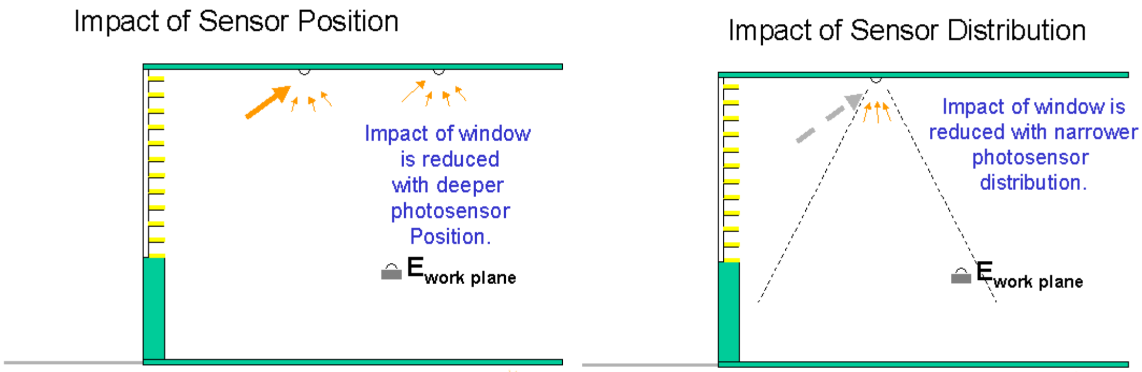


Figure 4. Variations in photosensor signal to work plane illuminance can be reduced by restricting the photosensor's view of a window. This can be done by locating the photosensor further from the window or by using a photosensor with a more restricted view of the space.

The Six Classrooms

The six classrooms that were considered in this modeling study are shown in Figures 5-10, which are data sheets for each of the spaces studied that include: their relevant dimensions, surface reflectances, daylight aperture sizes and locations, and glazing transmittances. The ceiling-mounted photosensor positions that were considered in this study are also shown on these data sheets. In each space, between two and five photosensor positions were considered. The photosensor systems are all ceiling-mounted photosensors with the photosensor oriented vertically within the space (aimed straight down toward the floor), except in Classroom 1, where a skylight well sensor was aimed in different directions. The photosensor is mounted at different distances from the perimeter daylight aperture to study sensor performance as the position relative to a vertical daylight aperture is changed.

The aim in selecting these spaces was to obtain a group of realistic daylight delivery systems that apply a variety of daylight delivery methods, daylight aperture conditions and luminance distributions in a classroom space. These classrooms provide the following range of conditions:

Classroom 1: Toplighting.
Classroom 2: Sidelighting with a long skylight well wall-wash system.
Classroom 3: Light shelf (interior and exterior).
Classroom 4: Sidelighting with a sloped ceiling and a north-facing clerestory on the wall opposite the window.
Classroom 5: Sidelighting (i.e., a window).
Classroom 6: Sidelighting on both north and south-exposure with skylights for lighting the interior of this modular classroom.

In all cases except Classroom 3, the designs are real-world classrooms located within the state of California. Some of these spaces have been studied with minor changes in glazing or room parameters compared to their real-world counterparts. All spaces were assumed to be oriented with the primary window glazing facing south, except Classroom 5, which was also modeled with its window facing north.

Classrooms 1 through 5 contain approximately 960 ft2 of floor area, which is the state's minimum requirement, while classroom 6, a modular unit, has a slightly larger floor area.

Almost all of the classrooms studied were separately studied with a direct and an indirect electric lighting system to address the issue of lighting system distribution type and its impact on the photosensor signal. For a ceiling-mounted photosensor, the direct contribution from adjacent indirect lighting equipment can provide a relatively higher photosensor signal. The magnitude of this signal will obviously depend on the sensor spatial distribution, on the sensor location relative to the luminaire, and on the luminaire's photometric distribution. The luminance patterns within the space and the impact of a dimmed lighting zone at the work plane are also likely to differ between a direct and an indirect lighting system.

While these spaces are not optimized for daylight performance, they provide representative conditions that are useful for testing the performance of photosensor control systems. Real-world designs encompass a wide variety of configurations, with daylight conditions that are likely to be represented by one of these six spaces.

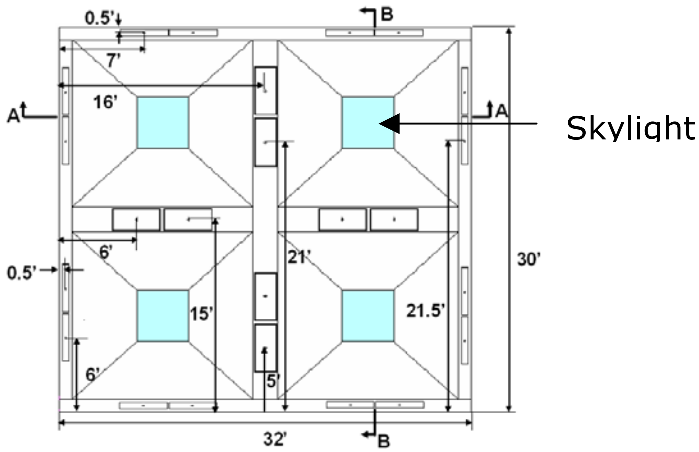
Computer Modeling Details

Desktop Radiance

The analysis of photosensor system performance was conducted using the Desktop Radiance 2.0b software. This is a MS Windows version of the Radiance software developed by Lawrence Berkeley National Laboratory (LBNL). The Radiance software is one of the most advanced lighting and daylighting analysis tools available. To analyze each of these spaces in Desktop Radiance, the room geometry was first described in AutoCAD using 3Dfaces (3-D polygons). Reflective or transmissive materials were then assigned to each of the surfaces. Work plane analysis grids were placed in the spaces for the analysis of desktop illuminance, and photosensor locations were entered as view points to create rendered images using a fish-eye view of the space. These renderings capture the room surface luminance patterns as seen from the photosensor.

The Desktop Radiance software permits the user to calculate the signal received by a photosensor of arbitrary distribution using fish-eye views created at a designated photosensor position. These views, which are stored in Radiance .PIC files, contain the luminance of each pixel in the image. The Radiance PSENS program was then used to compute the photosensor signal that would occur for a particular photosensor spatial distribution by entering a file of specified format. This spatial distribution file contains the relative sensitivity of the photosensor for all directions of incident light arriving at the photosensor. A sample view file and a sample photosensor file are shown in the schematic provided in Figure 11. The PSENS program multiplies the sensor sensitivity times the luminance in each direction to determine the resulting photosensor signal. A photosensor that responds to incident light like a standard cosine-

Figure 3: Classroom 1 - Toplighting



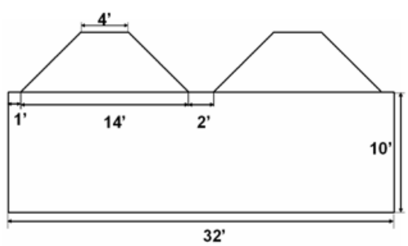
Plan View with luminaires

Ceiling reflectance: 75%
Wall reflectance: 60%
Floor reflectance: 30%

Skylight Transmittance: 40% diffuse

Photosensor Locations:
- V1: 15,15,10 (0,0,-1)*
- V2: 24,3.5,12.5 (0,1,0)
- V3: 24,13.67,10 (0,0,1)
- V4: 24,9.5,14.5 (0,0,1)

* Values in parentheses represent the direction vector that the photosensor faces.



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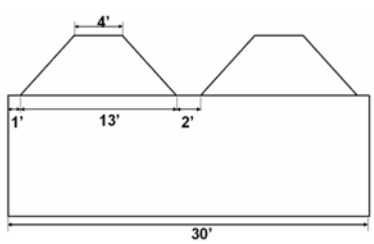

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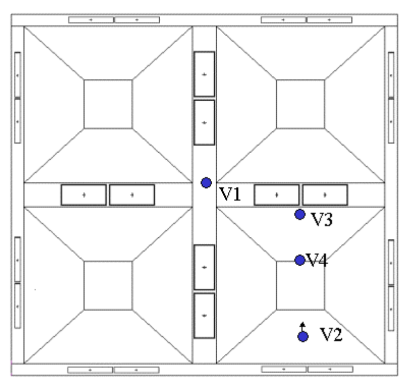
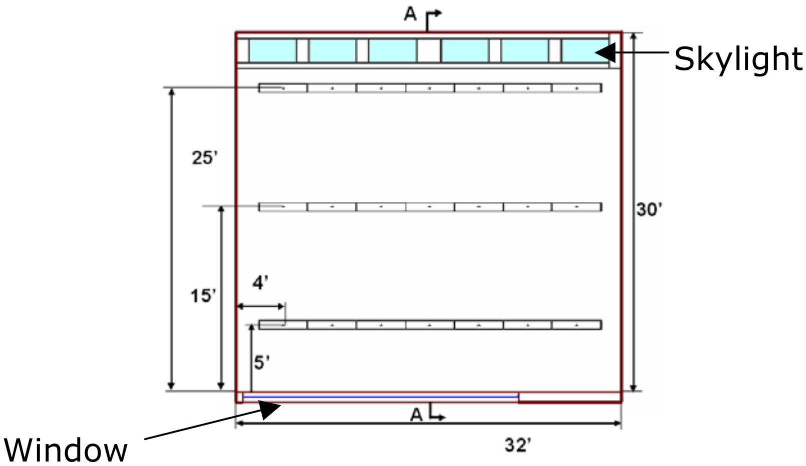


Photosensor locations

Figure 4: Classroom 2 – Sidelighting with Linear Skylight Well



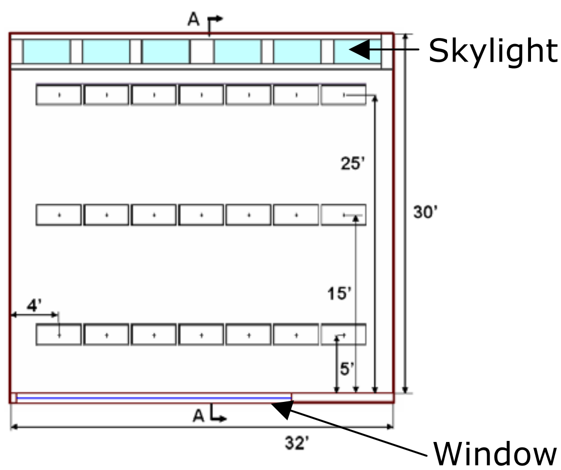
Plan View - Wrap

Ceiling Reflectance: 80%
Wall Reflectance: 73%
Floor Reflectance: 31%

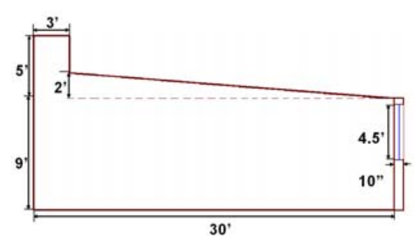
Window Transmittance: 62%
Window Reflectance: 8%

Skylight Transmittance: 40% diffuse

Photosensor Locations (inches):
- V1: 10, 7.5, 9.53
- V2: 10, 10, 9.7
- V3: 10, 20, 10.45



Plan View - Troffer



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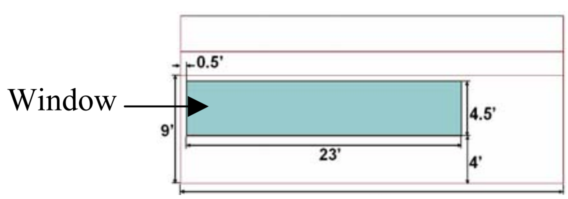
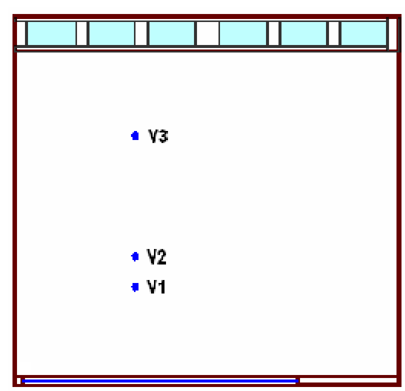
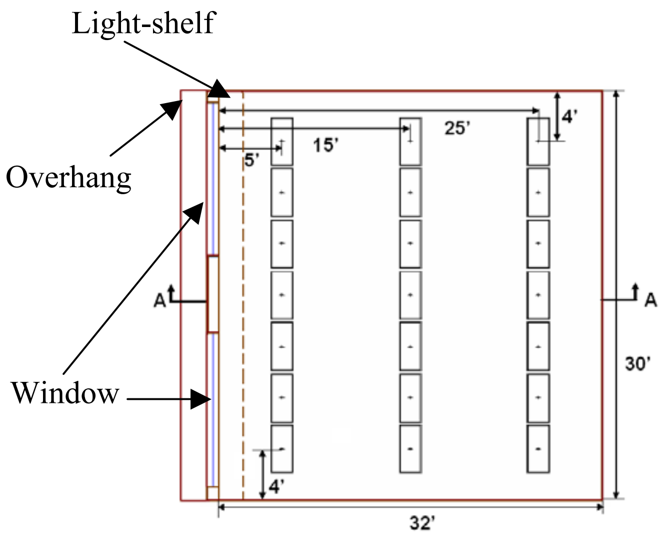


South Elevation View



Photosensor Locations

Figure 5: Classroom 3: Light Shelf



Plan View

Ceiling Reflectance: 84%
Wall Reflectance: 74%
Floor Reflectance: 32%

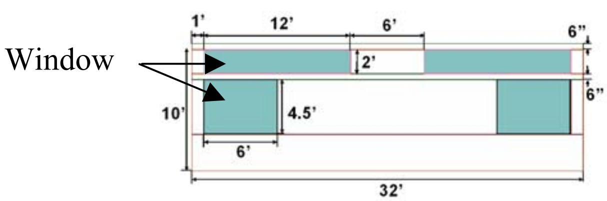
Lightshelf Reflectance (Exterior): 62%
Exterior Wall Reflectance: 39%

Lower Window Transmittance: 62%
Lower Window Reflectance: 12%

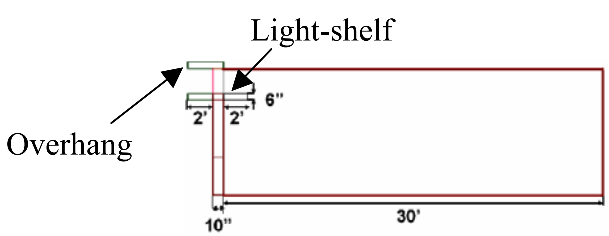
Upper Window Transmittance: 88%

Upper Window Reflectance: 12%

Photosensor Locations (inches):
V1: 10, 16, 10.5
V2: 6, 16, 10.5
V3: 10, 8, 10.5
V4: 6, 8, 10.5
V5: 14, 8, 10.5



South Elevation View



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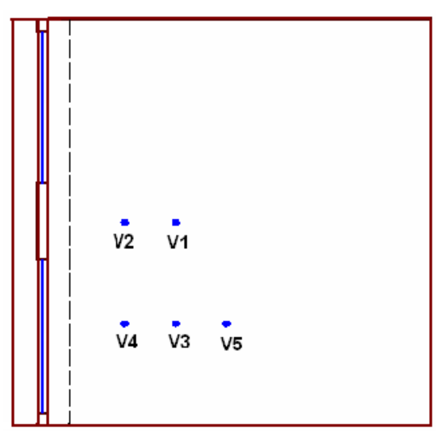
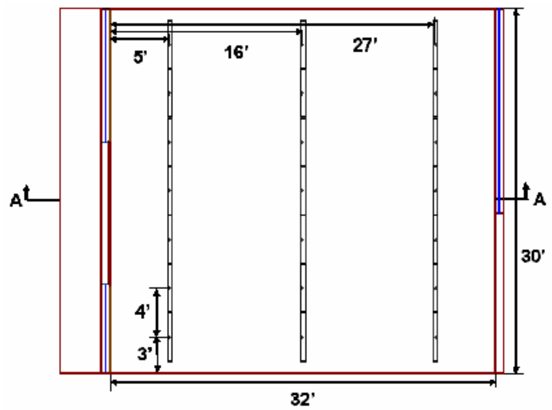


Photosensor locations

Figure 6: Classroom 4: Sidelighting and Clerestory



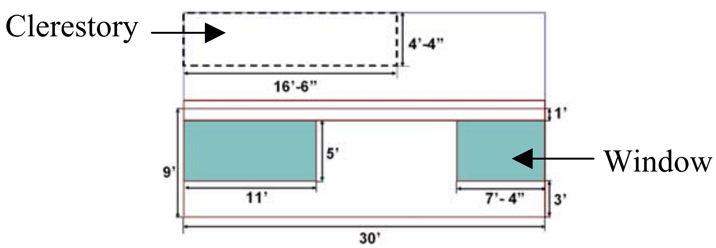
Plan View

Ceiling Reflectance: 84%
Wall Reflectance: 74%
Floor Reflectance: 32%

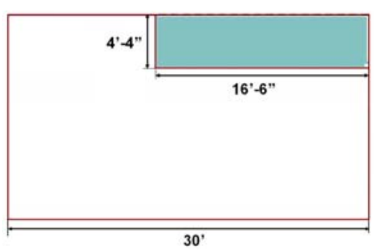
Exterior Wall Reflectance: 70%

Window Transmittance: 62%*
Window Reflectance: 12%
*view window and clerestory

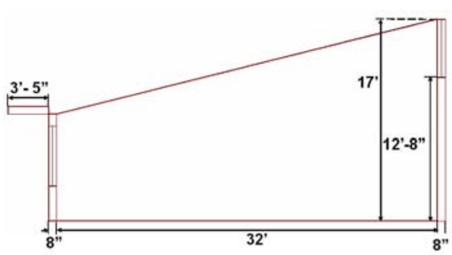
Photosensor Locations (inches):
V1: 6, 15, 10.4
V2: 12, 15, 11.9
V3: 18, 15, 13.4
V4: 24, 15, 14.9



South Elevation View



North Elevation View



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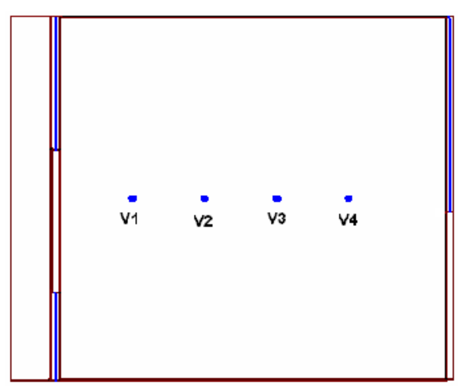
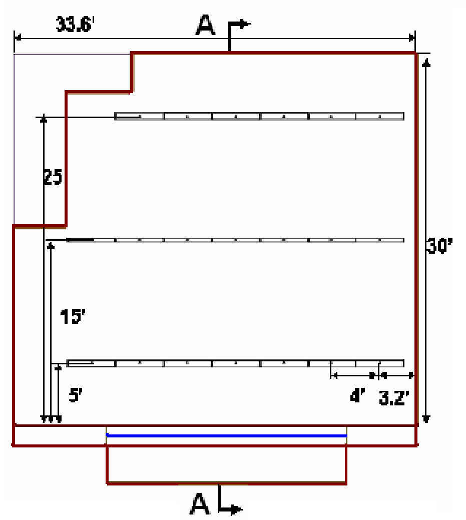


Photosensor locations

Figure 7: Classroom 5: Sidelighting

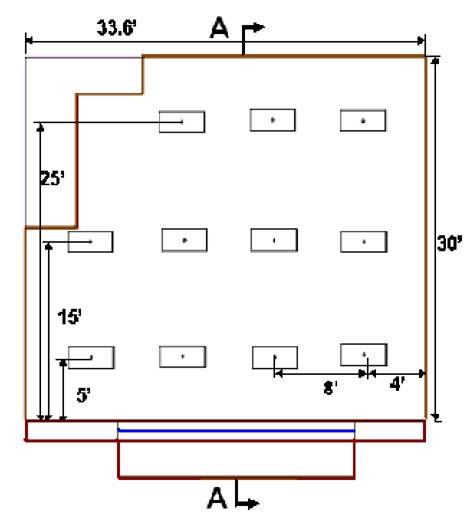


Plan View - Troffer

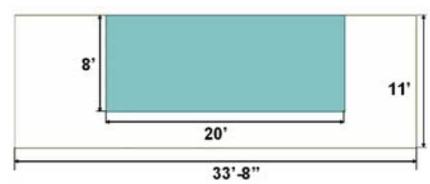
Ceiling Reflectance: 84%
Wall Reflectance: 74%
Floor Reflectance: 32%
Exterior Wall Reflectance: 56%

Window Transmittance: 62%
Window Reflectance: 12%

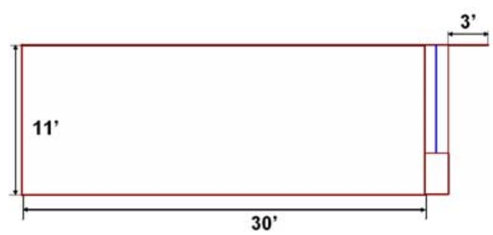
Photosensor Locations (inches):
V1: 16, 6, 10.08
V2: 16, 12, 10.08
V3: 16, 18, 10.08
V4: 16, 24, 10.08



Plan View - Wrap



South Elevation View



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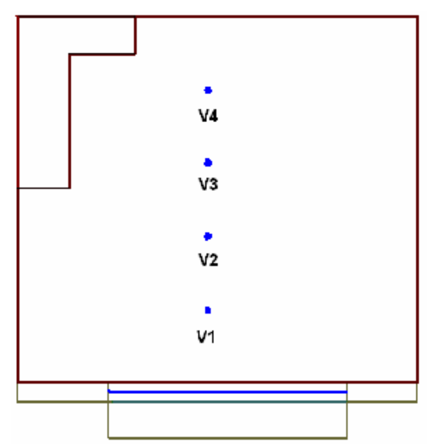
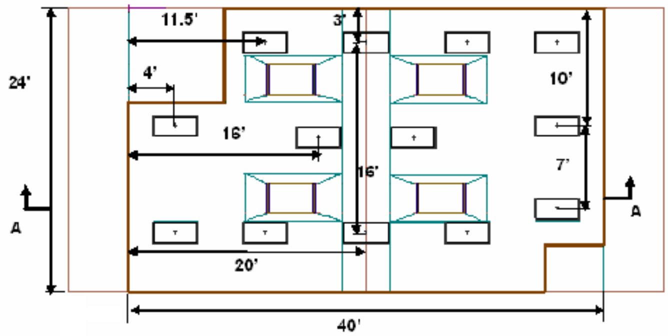


Photosensor locations

Figure 8: Classroom 6: Sidelighting and Toplighting

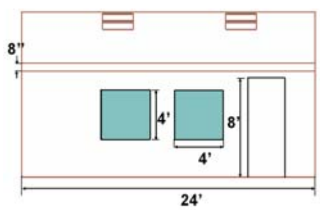


Plan View

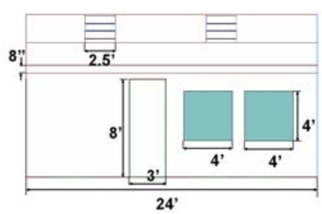
Ceiling Reflectance: 80%
Wall Reflectance: 74%
Floor Reflectance: 30%
Exterior Wall Reflectance: 56%

Window Transmittance: 62%
Window Reflectance: 12%

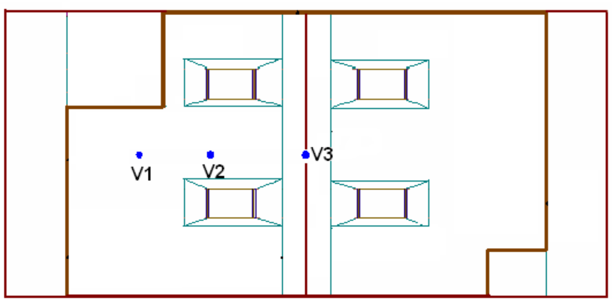
Photosensor Locations:
V1: 6, 12, 8.96
V2: 12, 12, 9.81
V3: 20, 12, 10.98



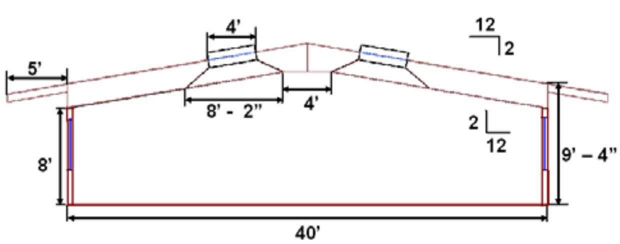
North Elevation View



South Elevation View



Photosensor locations



Section AA

corrected illuminance meter, which is one of the photosensor configurations tested in this study, would have a distribution that applies a cosine function at each vertical angle. This function is applied across all horizontal (azimuth) angles for this sensor.

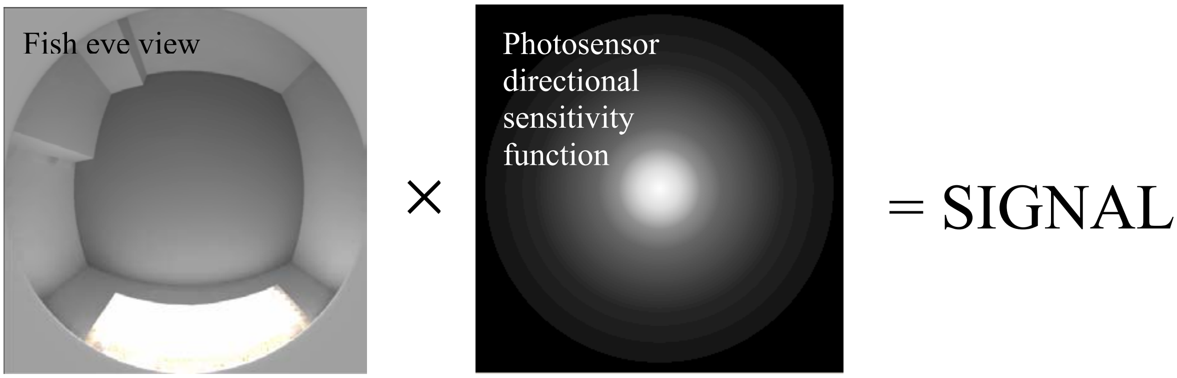


Figure 11. Schematic showing how the PSENS program integrates a fish-eye image (left) with the photosensor spatial sensitivity (right) to arrive at the photosensor signal.

The general runtime parameters applied in the Desktop Radiance analyses (rendered views and analysis grids) are as follows:

```
render= -ab 5 -av 0 0 0 -ds 0.1 -dj 0.8 -dt 0 -dc 0.5 -dr 1 -dp 512 -sj 1
-st 0 -ar 700
```

These parameters generally provide relatively smooth luminance patterns in the images, and result in reasonable execution times (generally in the range of 1-3 hours per run or less).

Glazing areas were addressed using mkillum surfaces in Radiance for all daylight apertures. This process creates a photometric distribution for each polygon that has been assigned to a window opening. Blinds and the actual glazing material were placed on the outside of the mkillum surface to consider their effect in the mkillum photometric distributions. This process speeds up the analysis and improves the overall smoothness of the luminance patterns in a space. In cases where a window was shaded by an overhang, the windows were subdivided into smaller polygons in the computer model to permit different vertical sections of the window to possess a different photometric distribution to account for shadowing and different views of the sky seen from each section of the window.

Daylight Conditions Modeled

In modeling these spaces, we performed separate analyses for the following sources of light:

1. Daylight from vertical window glazing
2. Daylight through clerestories or skylights, and
3. The electric lighting system, with each row of luminaires considered separately.

Skylights and clerestories were separated from the vertical glazing to allow the transmittance of each glazing type to be separately modified without requiring additional analysis. Rows of luminaires were considered individually to permit the analysis of a dimmed zone that consisted of one, two or three rows of luminaires. For each photosensor position, a separate fish-eye rendered image was created for each of these sources of light. The different daylight conditions studied were as follows:

(1) A clear sky
(2) An intermediate (partly cloudy) sky.
(3) A CIE overcast sky

The clear and intermediate skies were considered at the following dates and times: January 21, March 21 and May 21 at 9AM, 10:30AM and 12 noon solar time. Afternoon times were not considered since only south and north-facing glazing conditions were applied. Afternoon times would present mirror images of the morning solar positions in most of the rooms.

The overcast sky considered was for March 21 at noon. Only a single overcast sky was evaluated because the daylight distribution under any overcast skies is similar, varying only in the magnitude of illuminance provided (which varies with the altitude angle of the sun at that time). That is, the standard overcast sky has the same relative luminance distribution at all points in the sky at all times of the year; so only one condition needs to be studied. The daylight factor, the ratio of the interior to exterior horizontal illuminance, is generally used to quantify daylight system performance under an overcast sky.

Whenever south-facing glass was present in a model, the windows were considered with three different blind conditions. These were:

1. no blinds (image preserving glass)
2. horizontal blinds
3. blinds oriented at a 30-degree angle, with the top surface facing outward to block direct sunlight from entering the space.

All blind conditions were considered for each of the three sky conditions mentioned above, and at each of the three times of the day. The only south-facing window not provided with blinds was the glazing located above the light shelf in Classroom 3.

Daylight conditions where direct sunlight entered a space either through a clear window or between the slats of the blinds were included in all analyses. In a typical classroom, a teacher may at times adjust the blinds to eliminate these conditions, but in the event direct sunlight is allowed to enter a space, we also analyzed the performance of the photosensors under these direct sunlight conditions.

In total, for each photosensor position within each space, 30 different sky and blind combinations were tested, as well as 6 different electric lighting conditions - one for each row, for each of the two luminaire types.

Photosensor Views
Fish-eye views of the space, as seen by the photosensor, were created for a number of different photosensor positions (viewpoints) within each space. These positions are shown on the Room Data Sheets, Figures, 5-10. A view file (.PIC file) was generated for each of the thirty daylight

conditions and for the six electric lighting conditions (the single rows of troffers and pendants) in each of the classroom spaces. For rooms with a flat ceiling, these views encompassed only a hemisphere of data, since the new photosensor design was not expected to have a view that exceeded a full hemisphere. For rooms with a sloped ceiling, the view considered a full sphere of data to allow for the potential study of a tilted photosensor in these spaces. To enable faster processing of these images, most of the sensor views were constructed at a resolution of 300 x 300 pixels.

For some of the view positions studied, the photosensor was positioned very near one of the pendant luminaires. View positions were assigned to gather data on sensor performance at a variety of different distances from the window and were not optimized relative to the electric lighting systems. This arrangement permits the electric lighting contribution to be compared to the daylight contribution for a variety of different conditions. Some of these positions, while they may be acceptable for tracking the daylight alone, may receive an electric light signal that is too high and be unacceptable if the electric lighting system's contribution to the sensor (that of the dimmed zone) is not separated from that of the daylighting system and any non-dimmed electric lighting zone.

Analysis Grids

In a similar manner, separate work plane illuminance grids were computed for each of the light sources mentioned above (the different daylight apertures and the different rows of electric light). Work plane grids were positioned at a height of 2.5 feet above the floor with the analysis points spaced 2 feet apart. The work plane grids permit the ratio of photosensor signal to work plane illuminance to be analyzed for any point on the work plane.

Analyzing the different rows of electric light separately also permits the study of different rows of luminaires being assigned to the dimmed lighting zone. For example, we can assign one, two or three rows to this zone using the data provided, and no additional Radiance runs are required.

Photosensors Tested

In this project, a number of different sensor configurations were tested. The Watt Stopper's (TWS) Model LS201 sensor, which was measured by LBNL, was studied along with a number of different prototype distributions. As you can see in the curves presented in Figure 12 for the sensors studied, the TWS LS201 sensor has a relatively narrow spatial distribution. The prototype sensors that were tested included a pure cosine sensor, which is a standard illuminance meter, and used to represent a sensor with a very wide field of view. For other fields of view, a series of cosine sensors with cutoff half angles of 45, 55 and 65 degrees were considered (See Figure 12). All sensors were axially symmetric to avoid problems with incorrect mounting that might occur with non-axially symmetric sensors. These sensors were considered to study the effects of wider and different fields of view on photosensor performance. Since a restricted view of the window and indirect lighting equipment is desirable, some form of cutoff distribution is generally necessary. This combination provided a range of photosensors to study, including very narrow (TWS), very wide (cosine) and a number of distributions between these extremes (the 45, 55 and 65-degree half angle sensors). A cosine response was considered for the cutoff sensors to model a photosensor that is wide and has an ideal cutoff condition.

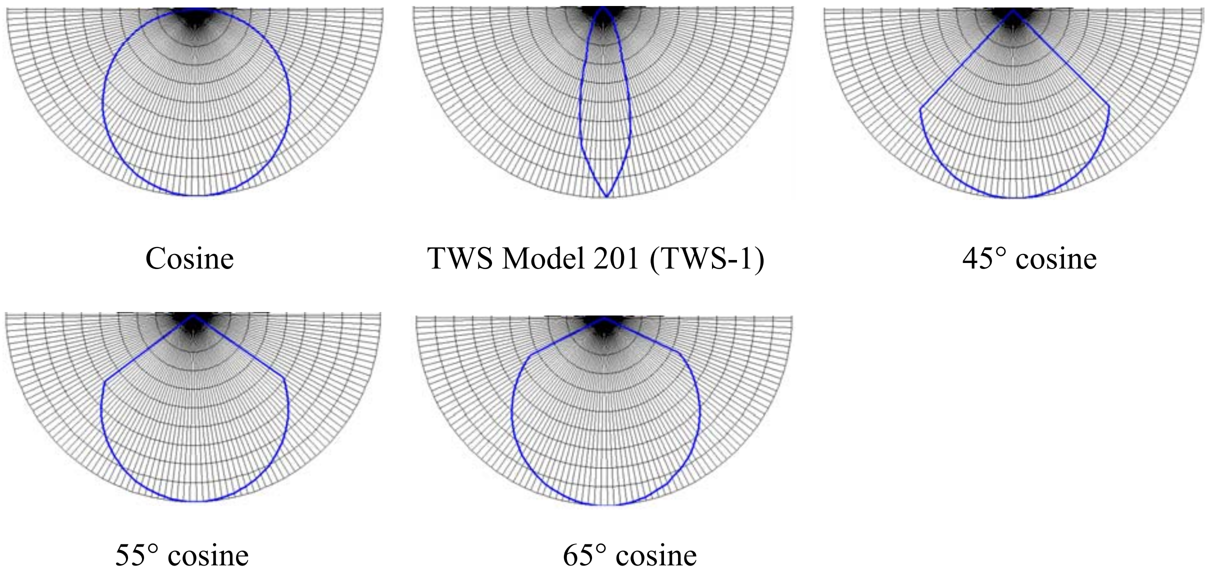


Figure 12. Photosensor spatial sensitivity distributions considered in this project. The degree range shown on three of the cosine photosensors is the half-angle to the cutoff point (beyond which the photosensor sensitivity is assumed to be zero).

Daylight System Performance in the Six Classroom Spaces

The graphs shown in Figures 13 through 18 provide information on the general performance of the daylight delivery systems in the six classroom spaces. Contour plots of the work plane illuminance are provided for an overcast sky with no blinds applied to the windows along with a few different sky conditions where blinds were applied to the windows. Daylight factors are listed on the overcast sky graphs. These performance graphs show that the daylight delivery systems in the six spaces do not generally provide uniform illuminance across these spaces. Workplane data such as these are important to study when laying out the electric lighting control system because they show where the daylight illuminance is comparatively low across the space. It would be reasonable to assign non-dimmed luminaires to the areas that have minimal daylight. Note that with indirect lighting the contribution to the workplane from a single non-dimmed luminaire is likely to be lower and spread out over a larger area due to the diffuse reflection from the ceiling.

In some daylight conditions presented in these graphs, you will see that abundant levels of daylight are provided, so that even the lowest values in the room meet the target illuminance of approximately 500 lux. At these conditions, the daylight distribution may still be non-uniform, with some areas in the room receiving much more than the target illuminance.

Finally, it is worth noting that some of the glazing configurations produce daylight distributions that do not adequately light the entire width of the space along an exterior wall. In these situations, effective design practice would dictate that the electric lighting in the regions that receive reduced amounts of daylight remain undimmed. Workplane locations at which the daylight illuminance is compared to the photosensor signal were generally not located within these areas.

Determining the Critical Point on the Work Plane Grid

In calibrating a photosensor system, it is necessary to correlate a photosensor signal with the dimming level required at a single point within a space for a typical daylight condition. To achieve proper performance, this point should be the point in the space that requires the highest dimming level setting to bring the illuminance up to the target task illuminance level, or to the illuminance level provided by the electric lighting system alone. That is, if the dimming level is set to provide the target illuminance at this task location, the target illuminance should be met at every other task location within the space. We will refer to this point on the work plane as the "critical point". The following discussion illustrates where this critical point is generally located within these spaces.

We can analyze the daylight and electric lighting system illuminance values on the work plane to determine the "critical point" at which the control system must maintain the target illuminance. The location of this point in a real space will depend on the location of the dimmed lighting zone, the contribution from any undimmed zone, and on the daylight delivery system applied. The critical point is generally located on the work plane in a position where the task illuminance provided by the combination of any daylight contribution and the portion of the electric lighting system that is not dimmed (i.e., the non-dimmed zone) will be farthest below the targeted workplane illuminance provided when the electric lighting system is at full output and there is no daylight present. This will generally be the point that has the lowest illuminance (due to daylight plus electric light from interior luminaires that are always on), excluding those points that are adjacent to the wall and may not receive the full target illuminance from the entire electric lighting system when no daylight is present. Note that in some spaces the entire electric lighting system may be dimmed, leaving no undimmed zone.

A study was performed to determine the location of the critical point along the centerline of the space and along a line halfway between the centerline and the side wall. The results are provided in Figures 19 and 20 for Classroom 5 for a dimmed lighting condition that consists of two rows of indirect luminaires. Information gained from these graphs can be used as guidance to those who will commission these photosensor systems to properly locate the critical point within a space.

For the spaces where daylight is admitted from the perimeter wall only, such as classrooms 3 and 5, an appropriate control zone might be to dim two of the three rows of luminaires, leaving the interior-most luminaire row on (and undimmed) at all times. In general for this condition, the location of the critical point is very near the middle row of luminaires – in some cases it falls one or two feet to the window side of this row, while in other cases it is directly beneath or one to two feet on the side opposite the window (Figures 19 and 20). When the slope of the daylight curve is falling off as you move away from the window, it is best to select a point on the inside end of the bottom of this curve. Therefore, we can state that the critical point in these situations should be located within two feet of the center row of luminaires when the first and second row are being dimmed. Obviously, a point closer to the side walls of the room (the walls that run

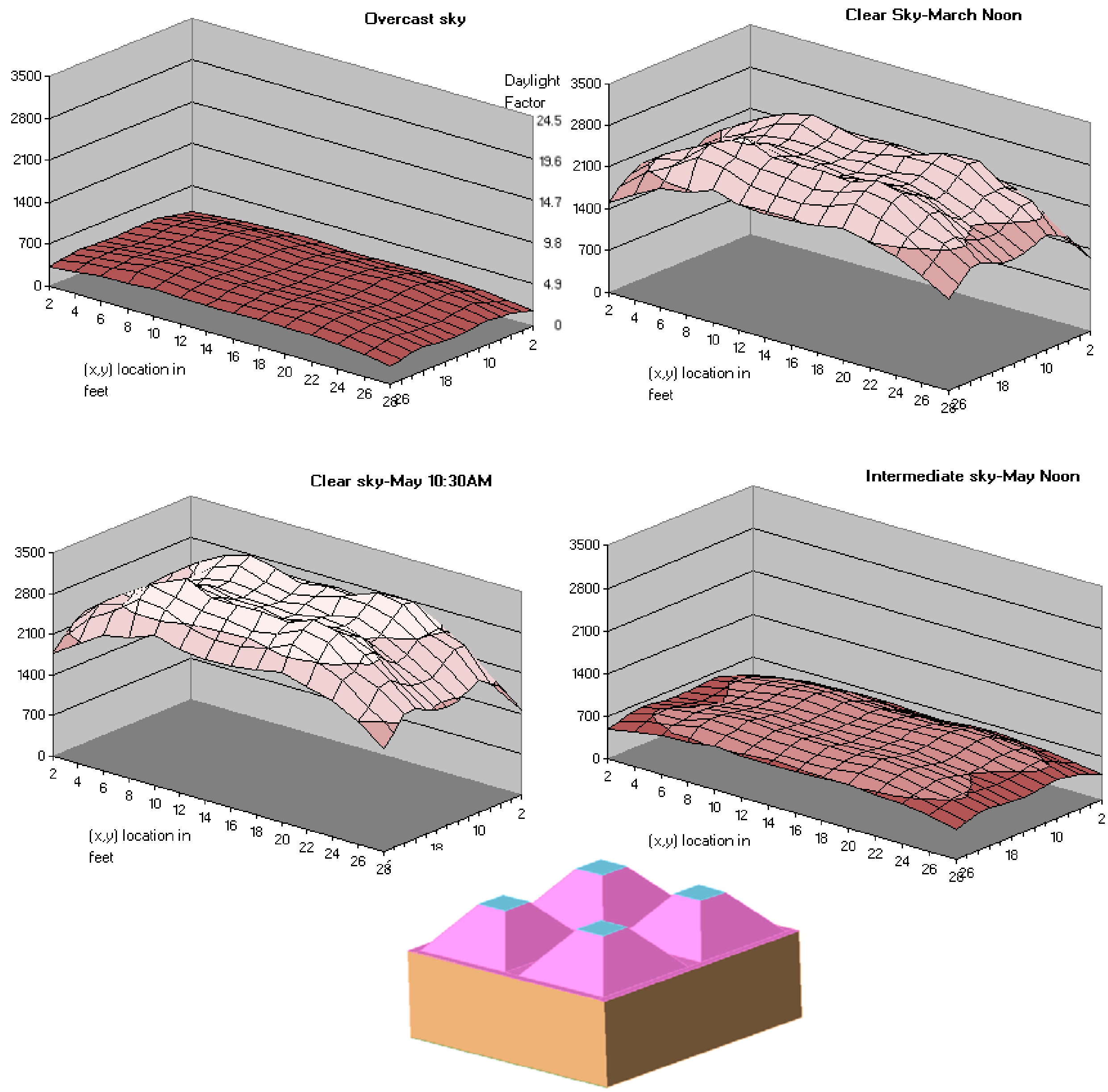


Figure 13. Illuminance contour graphs (in lux) for Classroom 1 at four different daylight conditions. Daylight factors are shown on the overcast sky graph.

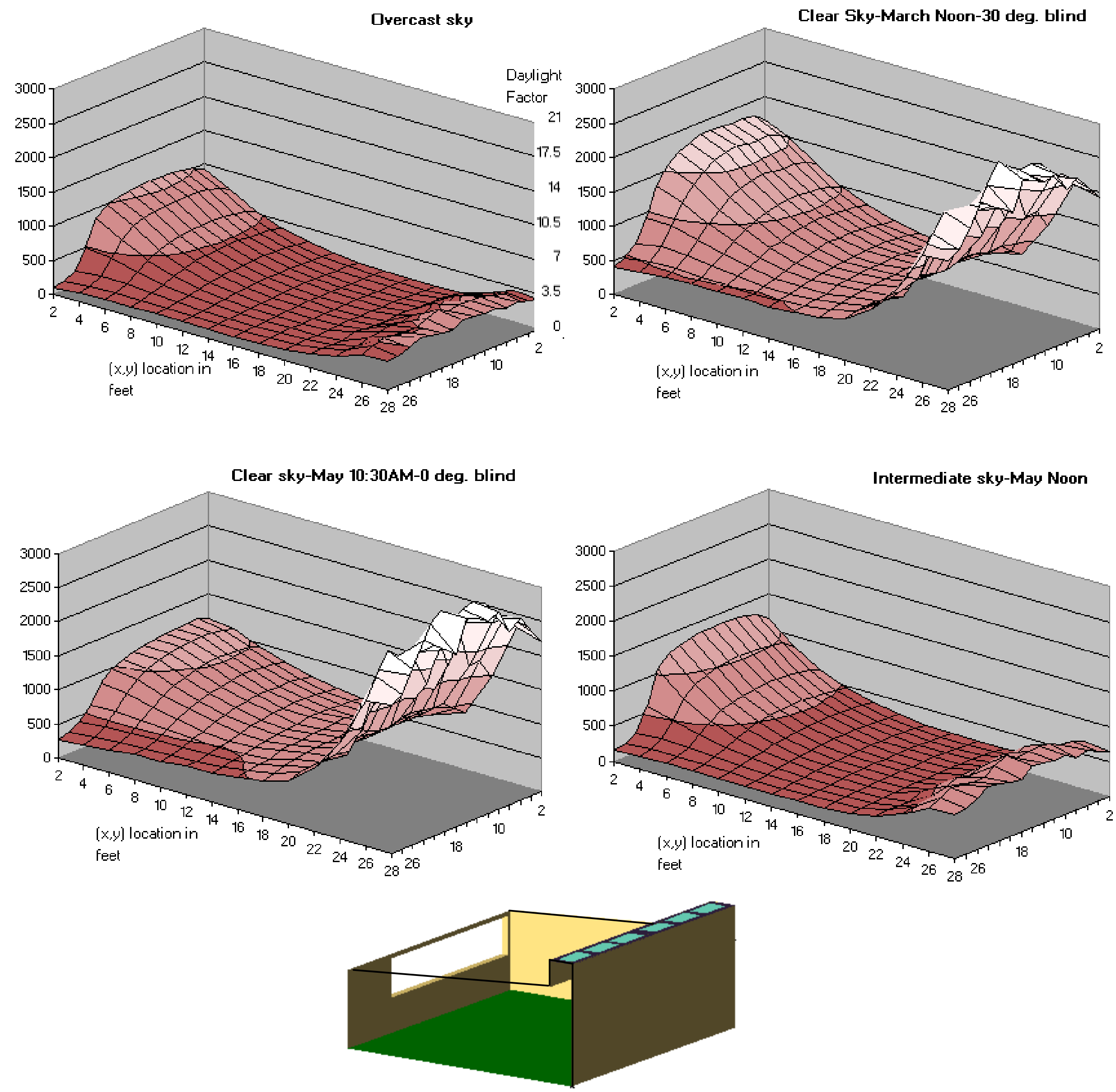


Figure 14. Illuminance contour graphs (in lux) for Classroom 2 at four different daylight and blind conditions. Daylight factors are shown on the overcast sky graph.

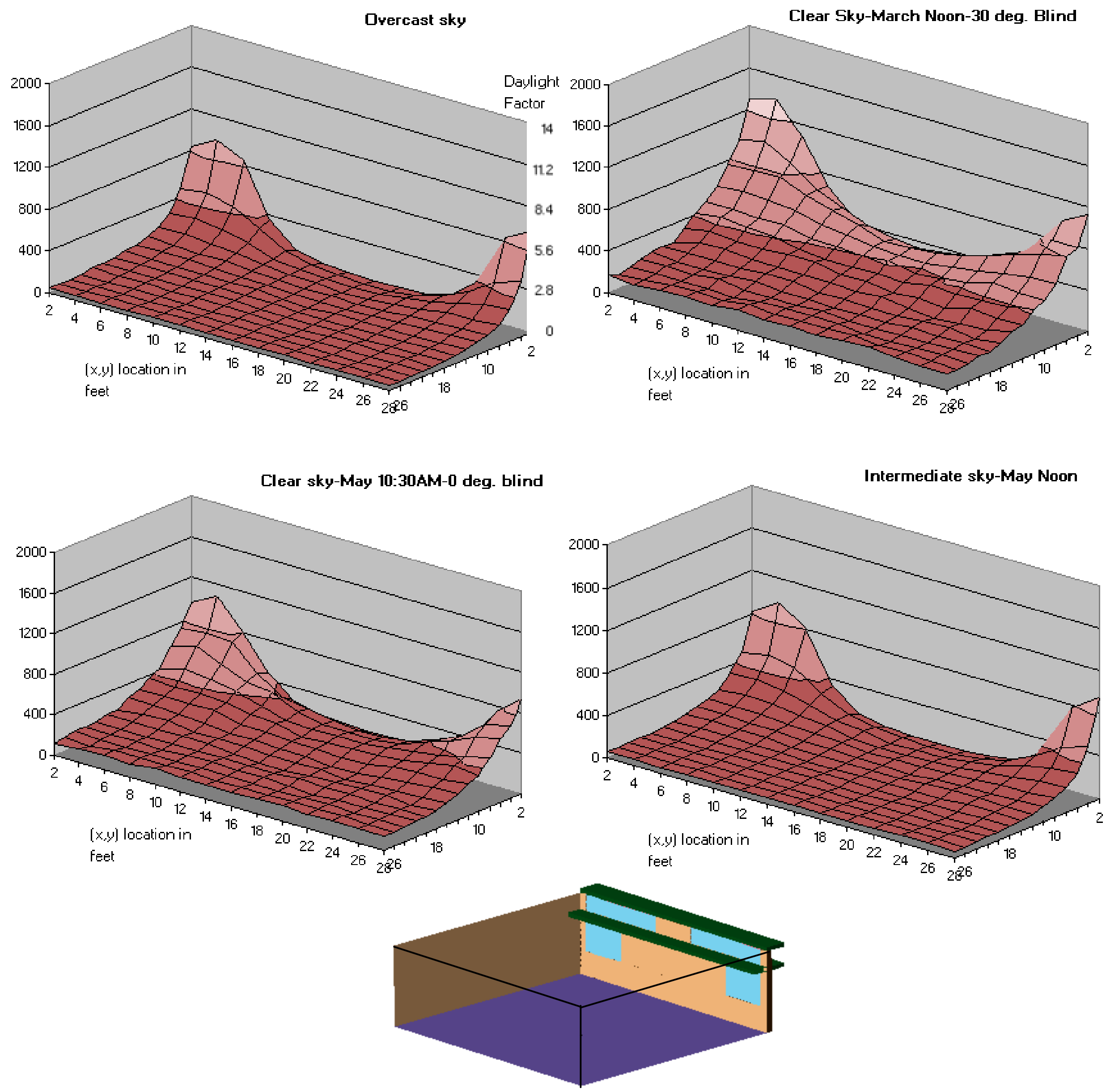


Figure 15. Illuminance contour graphs (in lux) for Classroom 3 at four different daylight and blind conditions. Daylight factors are shown on the overcast sky graph.

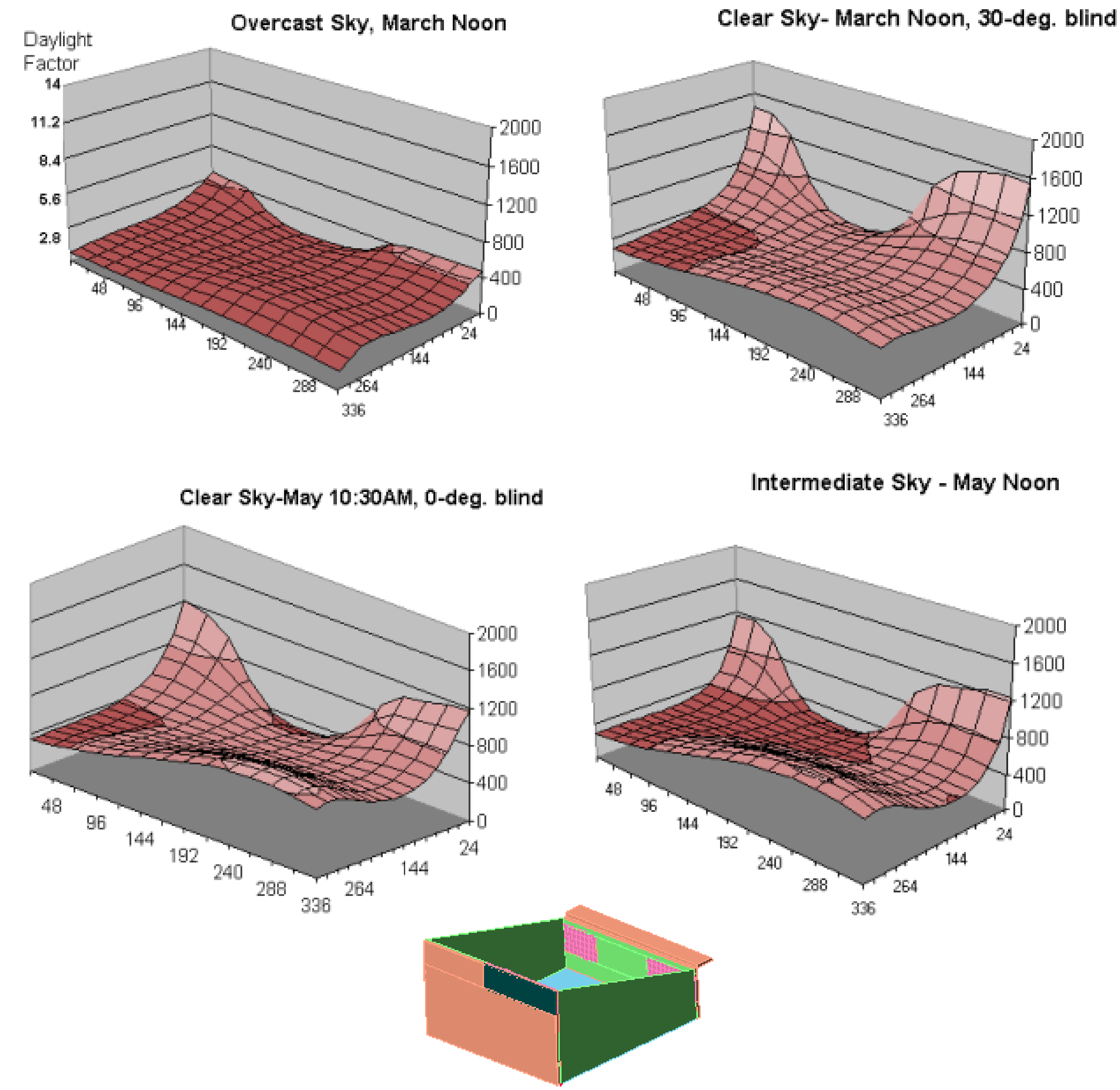


Figure 16. Illuminance contour graphs (in lux) for Classroom 4 at four different daylight and blind conditions. Daylight factors are shown on the overcast sky graph.

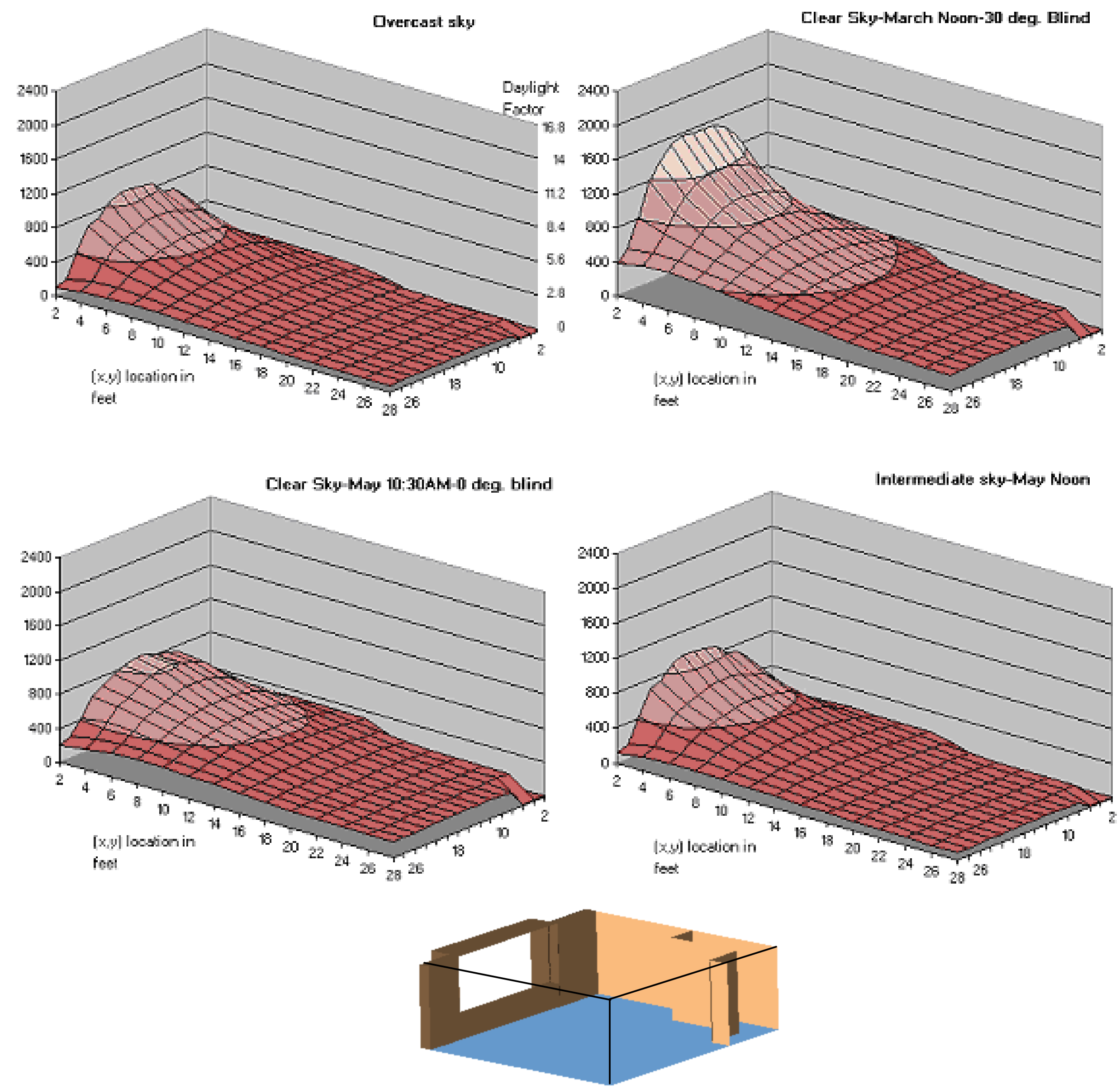


Figure 17. Illuminance contour graphs (in lux) for Classroom 5 at four different daylight and blind conditions. Daylight factors are shown on the overcast sky graph.

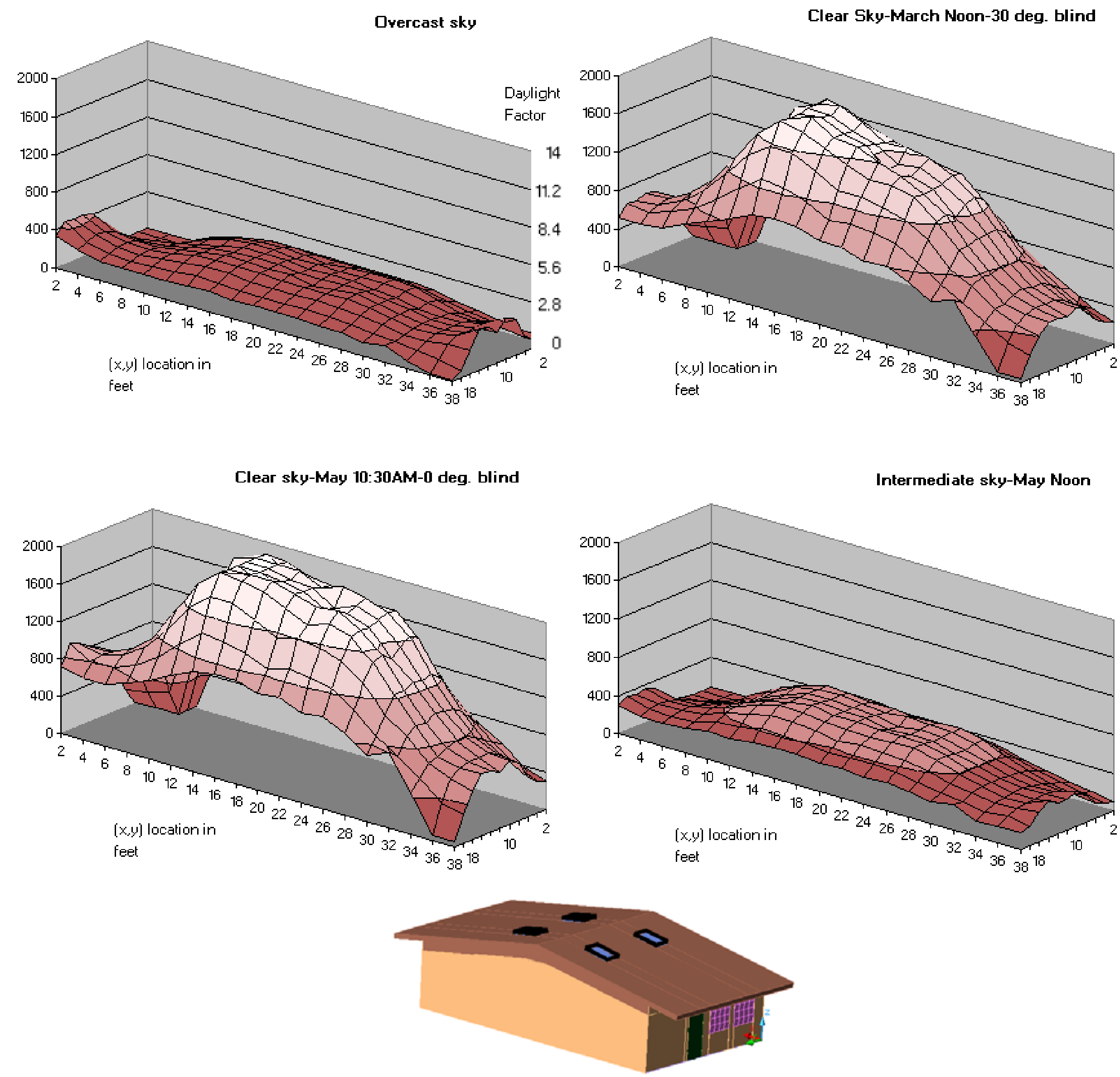


Figure 18. Illuminance contour graphs (in lux) for Classroom 6 at four different daylight and blind conditions. Daylight factors are shown on the overcast sky graph.

perpendicular to the windows) presents a slightly lower lighting condition than a point near the center. It would therefore be prudent to locate this point closer to the wall than to the center of the room, but still in an area where critical tasks will be performed. When selecting this point at calibration time, it would be best to place it on the side of the room that receives less daylight. That is, the view out the window should be away from the sun rather than toward the sun to address the target illuminance on the side of the room that receives less daylight.

It is important to note that the location of this critical point is independent of the location of the photosensor. Even if the photosensor is placed very near the window, the critical point to which it should be calibrated must be the point in the space within the controlled lighting zone at which it is most important to maintain the target illuminance. This is the point within the area, or at its perimeter, where the daylight, in combination with the luminaires that are not dimmed, is lowest relative to the target illuminance level (or to the level provided by the electric lighting system when all luminaires are at full output). This study shows that this point can usually be placed directly under the second dimmed row, plus or minus one or two feet, with reasonable results.

In an actual space, one can easily use an illuminance meter to properly locate this point or region on the work plane. The illuminance meter can be used to quickly locate the task point where the illuminance from both the daylight and any non-dimmed electric lighting system zone reaches a minimum by positioning the meter around a space. It is important to remember to turn on the non-dimmed zone and switch off the dimmed zone when searching for this point. In addition, a person searching for this point within a room should attempt to eliminate his/her body shadow from the illuminance meter reading.

Laying Out Control Zones

In the design of spaces with daylight, the portion of the lighting system that will be controlled by the photosensor must be assigned. To properly size such a system, one must study the distribution of daylight that is provided in the space under a variety of lighting conditions. Data similar to that shown in Figures 13 through 18 are helpful in this regard. In combination with this, it is important to also analyze the performance of the electric lighting system. As mentioned above, the control zone must supplement the daylight system, plus any portion of the electric lighting system that is likely to be on (generally that portion which is not controlled by the photosensor). At this time, no commercially available software is available that permits a designer to easily study these situations. Lighting software that performs both electric and daylight calculations can be applied by creating the necessary analysis runs – a few with daylight and a few with electric light. But it is not easy to combine these results to analyze combined performance, or to determine the desired dimming levels to estimate the amount of energy that such a system would save.

Classroom 1 presents a fairly straightforward situation for sizing the dimmed lighting zone, since the daylight is relatively uniform across the entire space. The large splayed wells should illuminate the walls relatively well, and it appears to be possible to dim the entire electric lighting system at one time. Still, it may be worthwhile to switch the luminaires that are against the chalkboard wall separately from the remainder of the space.

Figure 19. Illuminance through the center of the room due to daylight plus the contribution from the interior row of troffers for Classroom 5 showing the location of the critical point at approximately 14 to 16 feet from the window. (The dimmed zone, the two rows nearest the window, would need to be set to raise all points to the target level.)

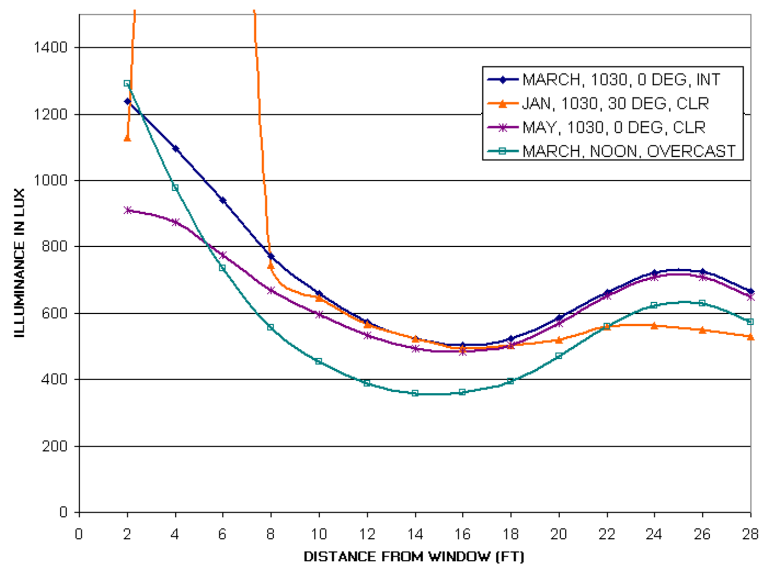
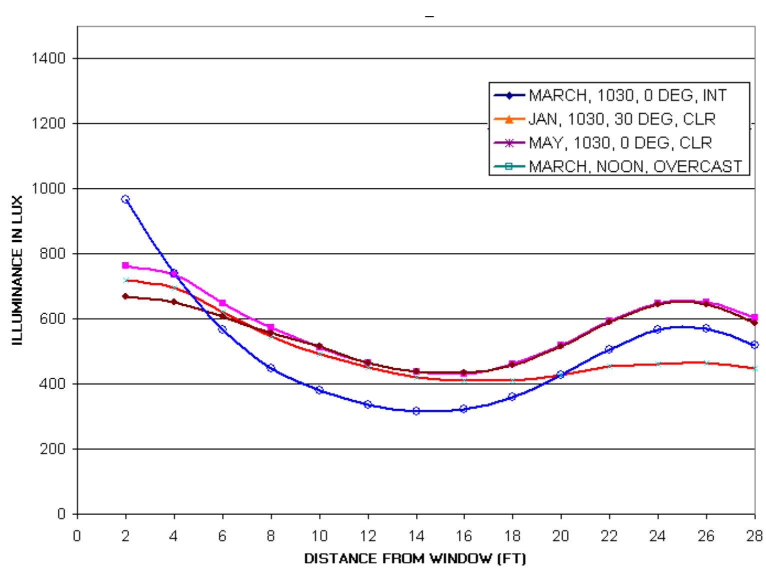


Figure 20. Illuminance at 6 feet from the east wall due to daylight plus the interior row of troffers for Classroom 5 showing the location of the critical point at approximately 14 to 16 feet from the window. (The dimmed zone, the two rows nearest the window, would need to be set to raise all points to the target level.)



In a situation like Classroom 5, which is described above, a decision would need to be made as to whether to dim one row of luminaires, two rows of luminaires, or the entire lighting system within the space. As you can see in the graphs provided in Figures 19 and 20, the dimming of two rows still permits a significant amount of dimming to occur at the sky conditions presented. Dimming of only one row would likely permit that row to be dimmed to minimum, whereas dimming three rows simultaneously would not allow the first two rows to reach their full potential. The dimming of two rows appears that it will allow both of these rows to be dimmed to a minimum, or near minimum, level for a large portion of the year.

Classrooms 2 and 4 present situations where daylight arrives from two different directions within the space. If a single dimmed zone is applied to classroom 2, it would appear best to apply it to the outer two rows of luminaires. However, the relative magnitude of the daylight produced by the skylights and the windows is not always the same, which could create some control problems. Two dimmed zones would be another possible solution, but two different photosensors would be needed. Also, because the window does not extend along the entire south wall, the entire first row of luminaires cannot be dimmed. Given the daylight configuration in Classroom 2, it may be necessary for this room have a chalkboard light, since little daylight will strike the side wall where the chalkboard is actually located.

Classroom 4 and 6 present rather complex situations where the critical point location would need to be determined based on the dimming zone that is applied. In classroom 4, the fact that the clerestory is not centered on the wall creates a somewhat darker corner within the room. The tall ceiling and indirect lighting system make it difficult to provide light to this dark corner, which is at the tall end of the room. If the clerestory extends across the entire wall, it may be possible to dim the electric light across the entire space, except that the blind position will impact the daylight along the shorter window wall. With a clerestory that spans the entire wall, under some situations the daylight would be at its lowest value (and represent the critical point for a dimming system that includes all luminaires) deep within the space under the clerestory. These occur when the sun is low in the sky in the wintertime. At other times, the low point will be in the center of the room. The latter occurs in the summer when the sun is high in the sky. Still, a conservative calibration condition could prevent this situation from presenting a problem if the entire electric lighting system is dimmed together. Room luminances should also be addressed before determining how to layout, control and calibrate the electric lighting system to ensure that a quality lighting condition is provided at all times.

Classroom 6 is a classroom that has both perimeter and skylight zones. In this space, the central area receives an abundance of daylight from the skylights, while the areas near the windows appear to receive slightly lower illuminance at most daylight conditions. This space could have one central dimmed zone, with the luminaires near the windows not dimmed, or two or three control zones, with one or two additional zones located near the windows. If only one perimeter zone is applied, it would be best to place it along the south side. It is unlikely that a single perimeter zone would work well if it controlled both the north and south perimeter luminaires.

Correlation between Photosensor Signal and Work Plane Illuminance

To analyze the performance of different photosensors and the impact of photosensor placement within a space, we investigated the correlation between the photosensor signal and the work plane illuminance for a range of photosensor positions. This study provides important data on how well a photosensor is capable of tracking the daylight illuminance provided on the work plane within these spaces. Performance was analyzed through graphical means by plotting the photosensor signal along the X-axis, and the work plane illuminance at a selected point (the critical point) on the Y-axis (see Figures 21 through 27 and Appendix A, which contains graphs for all of the classrooms studied). The vertical spread and the linearity of these data points are primary indicators of how well the photosensor would be able to control the electric light in a space.

The reason why the vertical spread is important is as follows. Assume two different daylight conditions provide an identical photosensor signal but the work plane illuminance at these daylight conditions differs by more than 10 fc. If the system is calibrated to work perfectly for one of these conditions, then it will experience approximately a 20% error in the resulting work plane illuminance provided by the dimming condition specified for the other condition. This may be acceptable as long as the system is calibrated at the condition that provides a lower work plane illuminance at this daylight signal. This is why a photosensor system should be calibrated at a condition that lies along the right side of one of these graphs - it will help to eliminate situations where insufficient illuminance is provided on the work plane due to differences in the ratio of photosensor signal to work plane illuminance. Points that lie along different lines when a line is drawn from that point to the origin have different ratios of photosensor signal to work plane illuminance. Whether or not the calibration condition will include direct sunlight in a space should be based on how the space and the blinds would be expected to be used. Typically, we may not be able to justify calibrating the system with direct sunlight in the space, so calibration should be performed with the blinds in place and angled so that the photosensor signal is somewhat maximized with respect to the daylight illuminance provided on the work plane.

For the graphs provided here and in Appendix A, the work plane illuminance point was located in the center of the room. This point is a reasonable location for the “critical point” at which the work plane illuminance is likely to drop below the target illuminance level when the innermost row of luminaires remains undimmed.

The data for each of these spaces provide similar results to what has been reported in other research studies on photosensors. As the photosensor is moved away from a vertical daylight aperture in its field of view, such as a window, the correlation between the photosensor signal and the work plane illuminance due to daylight improves. However, along with this improvement, the daylight signal also declines. This is important because if the photosensor’s contribution from the dimmed portion of the electric lighting system is greater than the daylight contribution, a conventional control algorithm that does not separate these two contributions would be difficult to apply. Problems will arise when the ratio of photosensor signal to work plane illuminance is higher for the electric light because it may be necessary for the photosensor signal to actually decrease as daylight is introduced to the space and the electric lighting system is dimmed. The only control algorithm that can likely function under this scenario is one where the electric lighting contribution for the dimmed zone is removed from the total signal to isolate the signal due to the daylight and any electric lighting system that is always on (such as an interior row of luminaires).

As you can see in Figure 22 the electric lighting signal is high when the photosensor is placed near a row of indirect luminaires. If the photosensor system is provided with the capability to subtract out the contribution of the dimmed luminaires, then photosensor placement is less critical, and even a position that receives a significant amount of direct light from an indirect luminaire would theoretically still provide acceptable performance. One problem with this type of system is that the electric lighting level is not constant – light will be lost as lamps age and as dirt accumulates on the luminaire. Steps should be taken to provide the most accurate estimation of the dimmed electric lighting settings if they are being subtracted from the photosensor signal. This might be done with a periodic nighttime automated recalibration of the electric lighting signal.

Impact of Sensor Position, Distribution and Direct Sunlight Entering a Space

As in previous studies on photosensor performance, the ability of a photosensor to accurately track the daylight in any of these spaces is impacted by the photosensor's view of the daylight apertures. For photosensors that are aimed downward, this would generally apply to the view of any windows. The cosine sensor, which has the widest view of any sensor studied, has the greatest spread in the plotted data (work plane illuminance versus photosensor signal) when mounted near the window. This is expected based on the findings of previous research studies. However, when this sensor is moved a sufficient distance away from the window, the agreement between photosensor signal and work plane illuminance improves significantly. We see similar results with the other sensors, although sensors with more narrow distributions have less spread in their data when mounted near the window, unless a patch of direct sunlight falls within its field of view. In the cases where direct sunlight is admitted to a space, the photosensor receives a much higher signal relative to the work plane illuminance, and the relative impact on a wider sensor appears to be less, although there may be situations where a wider photosensor distribution picks up direct sunlight while the narrower sensor would not.

It is important to note that much of the spread in the data on these photosensor signal correlation graphs is provided by the times, solar positions and blind conditions that permit direct sunlight to enter a space. These include all of the no-blind conditions when direct sunlight is striking the window. The reason for this is that the sensor sees a patch of very high luminance that is cast onto the floor (or walls) of the space, resulting in a much higher photosensor signal. This bright patch also contributes light to the work plane, but since the sunlight arriving at a work plane point (the critical point) must be reflected from other room surfaces, the relative magnitude of this contribution is much lower at the work plane than it is at the sensor. It is reasonable that an analysis point near the center of the room, as applied in these graphs, is not as strongly influenced by a patch of sunlight as is the photosensor, which has a direct view of a bright sunlight patch.

Therefore, it is clear why these points lie to the right of the other points on the photosensor performance graphs, indicating that a higher photosensor signal occurs for the same critical point work plane illuminance. Conditions where direct sunlight is admitted to the space are shown in Figure 28 for classroom 5 for the clear sky conditions. Since the intermediate sky also has a direct beam component, identical blind conditions and solar times for this sky type provide similar images, but with a reduced solar beam contribution.

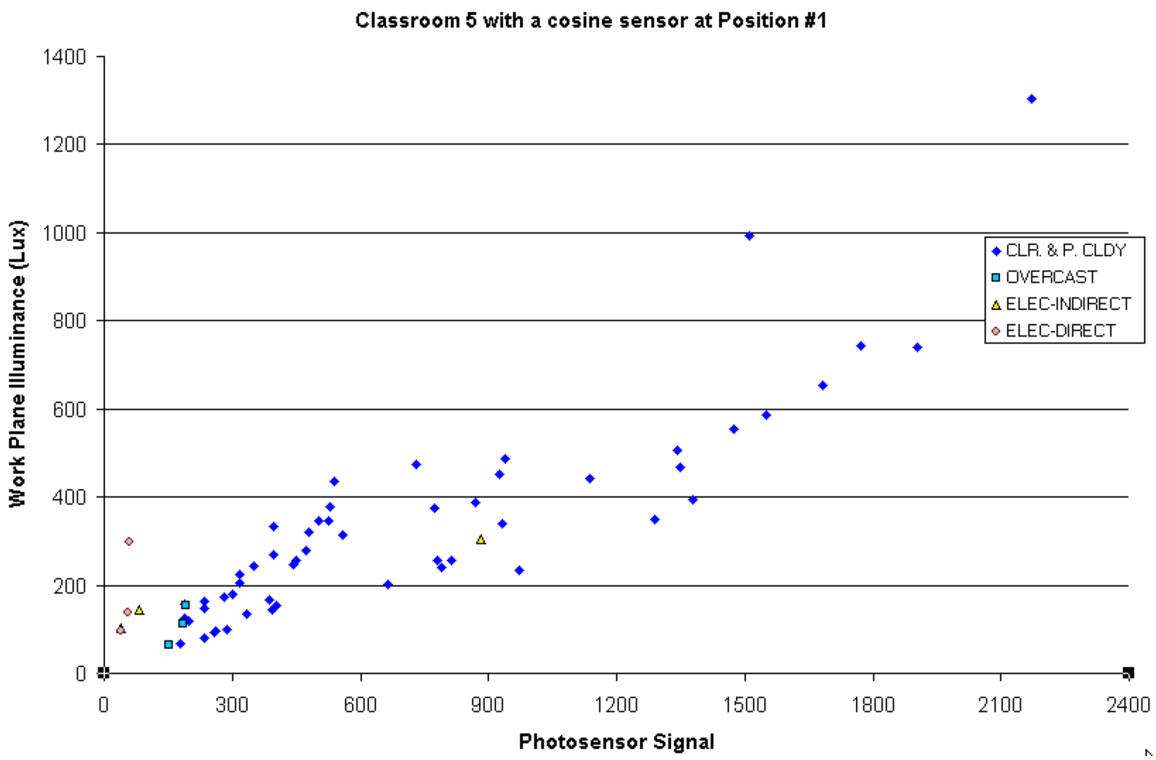


Figure 21. Graph of workplane illuminance versus photosensor signal for the Cosine Sensor in Classroom 5 at photosensor Position 1.

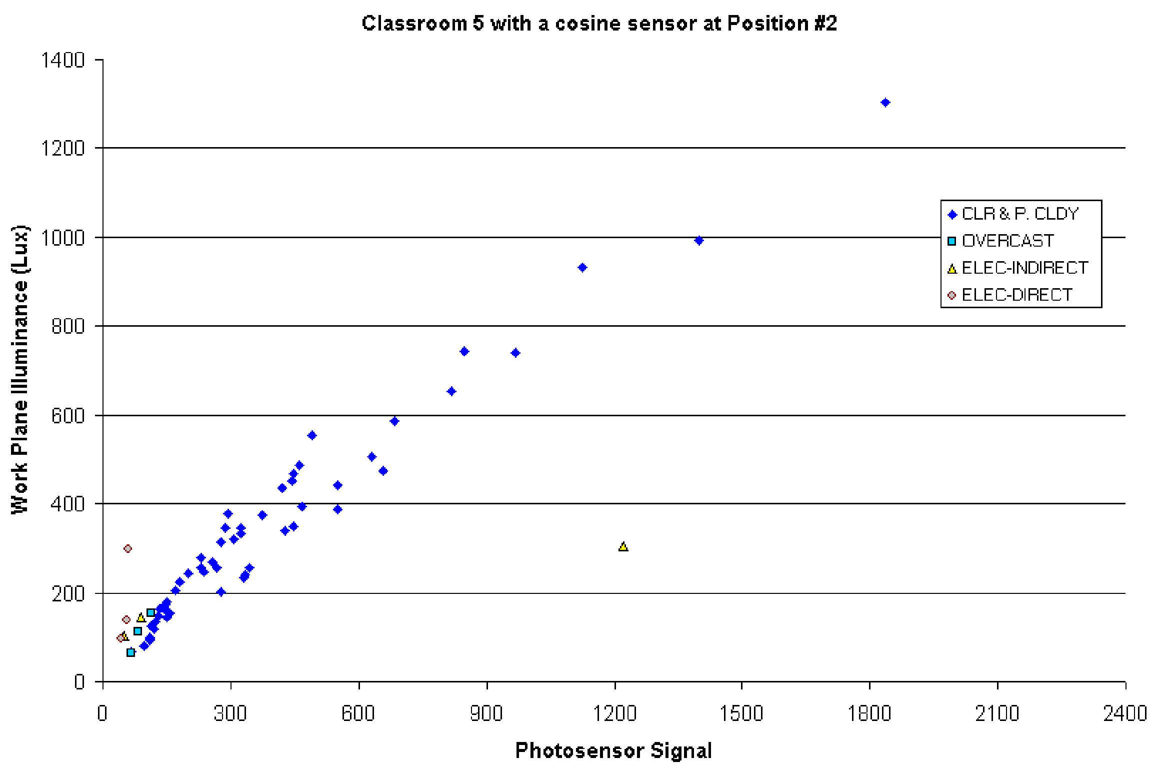


Figure 22. Graph of workplane illuminance versus photosensor signal for the Cosine Sensor in Classroom 5 at photosensor Position 2.

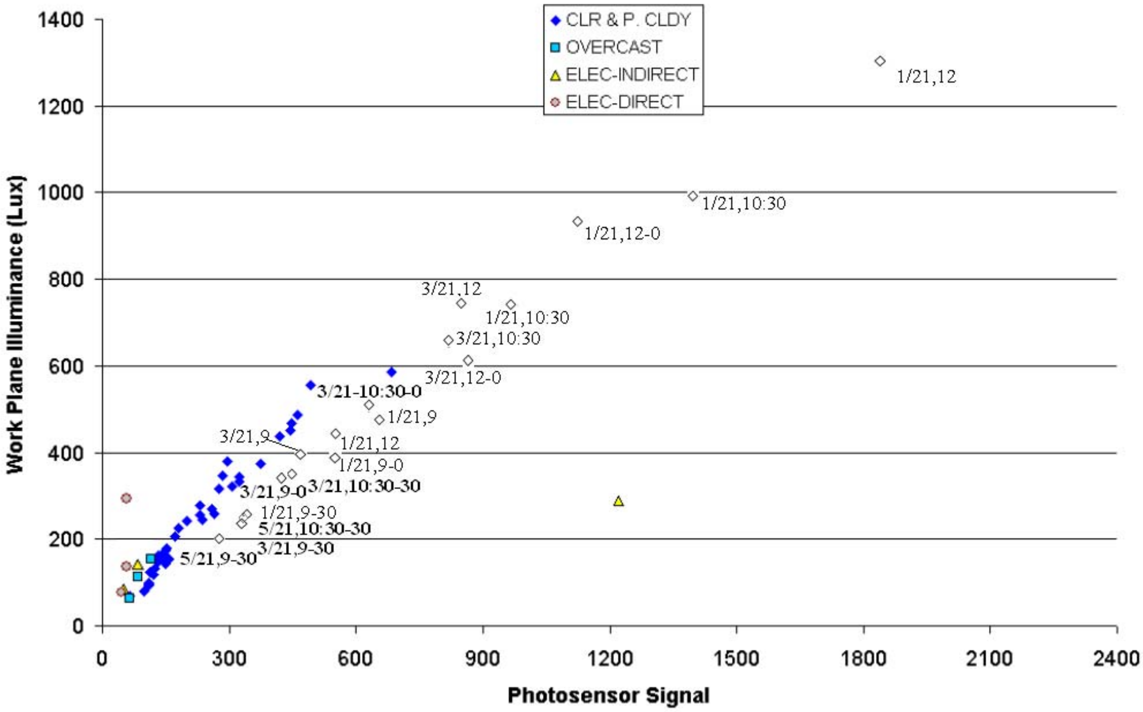


Figure 23. Graph of workplane illuminance versus photosensor signal for the Cosine Sensor in Classroom 5 at photosensor Position 2. Times and blind conditions are shown for points that lie to the right of the main cluster. Most of these are conditions where direct sunlight is admitted, but others are blind conditions where the sensor has a view of the bright top side of the blinds, or out through the blinds.

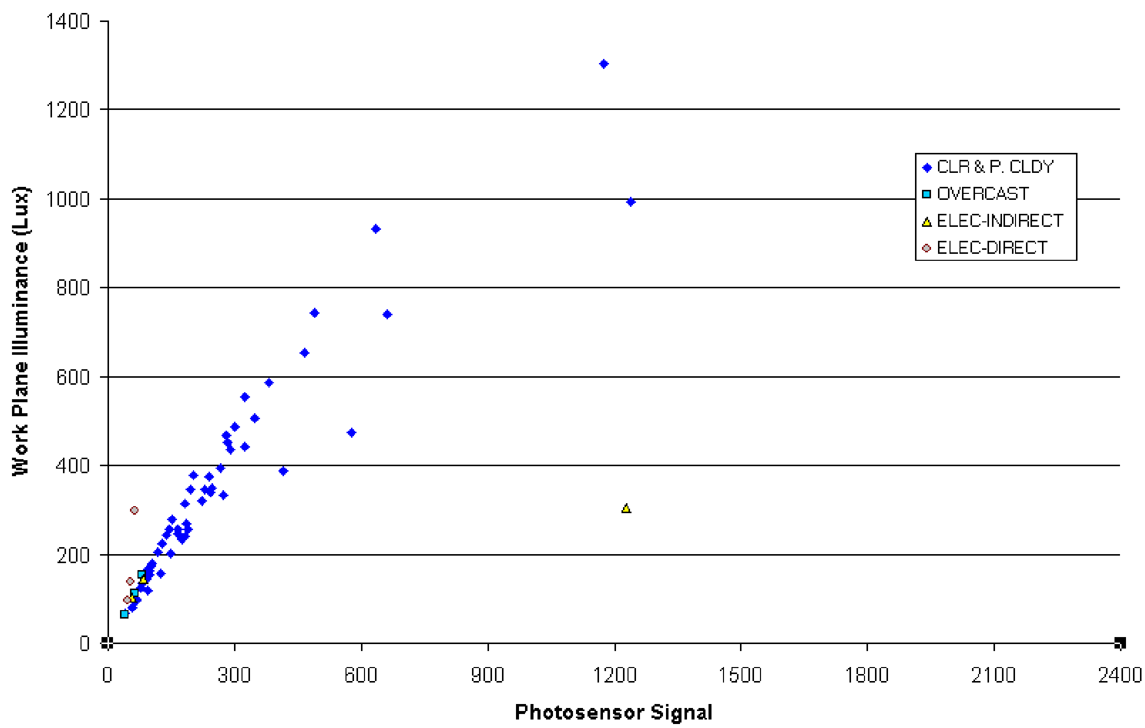


Figure 24. Graph of workplane illuminance versus photosensor signal for the Cosine Sensor in Classroom 5 at photosensor Position 3.

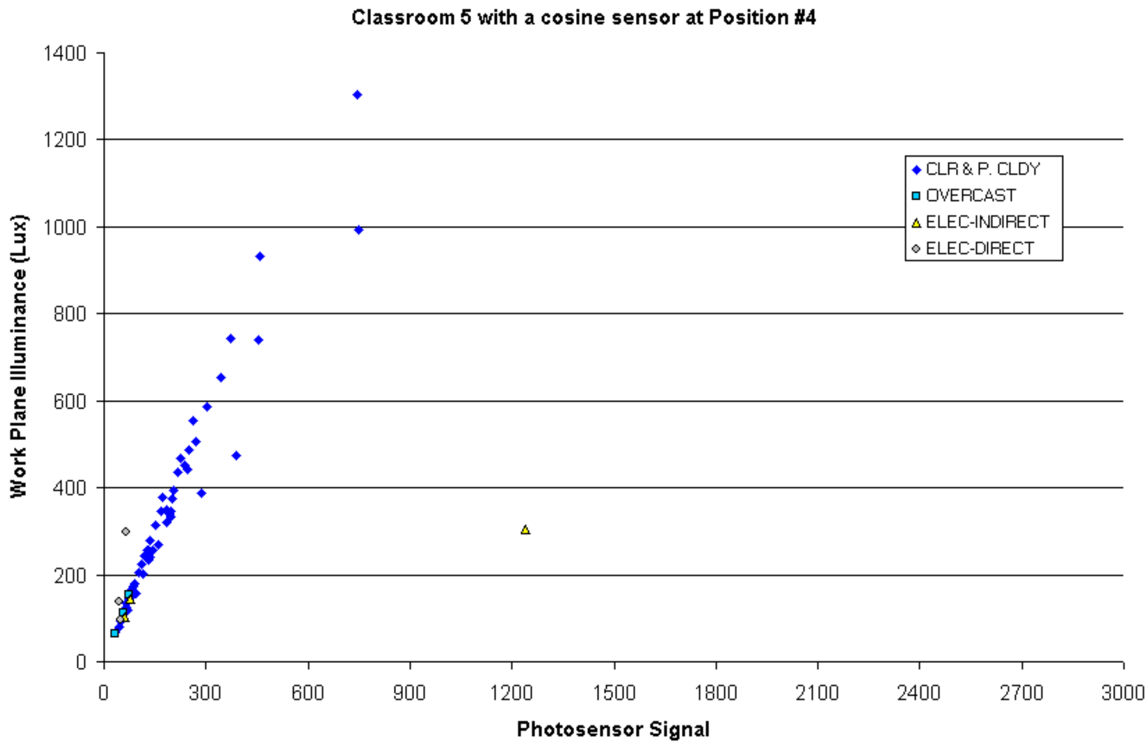


Figure 25. Graph of workplane illuminance versus photosensor signal for the Cosine Sensor in Classroom 5 at photosensor Position 4.

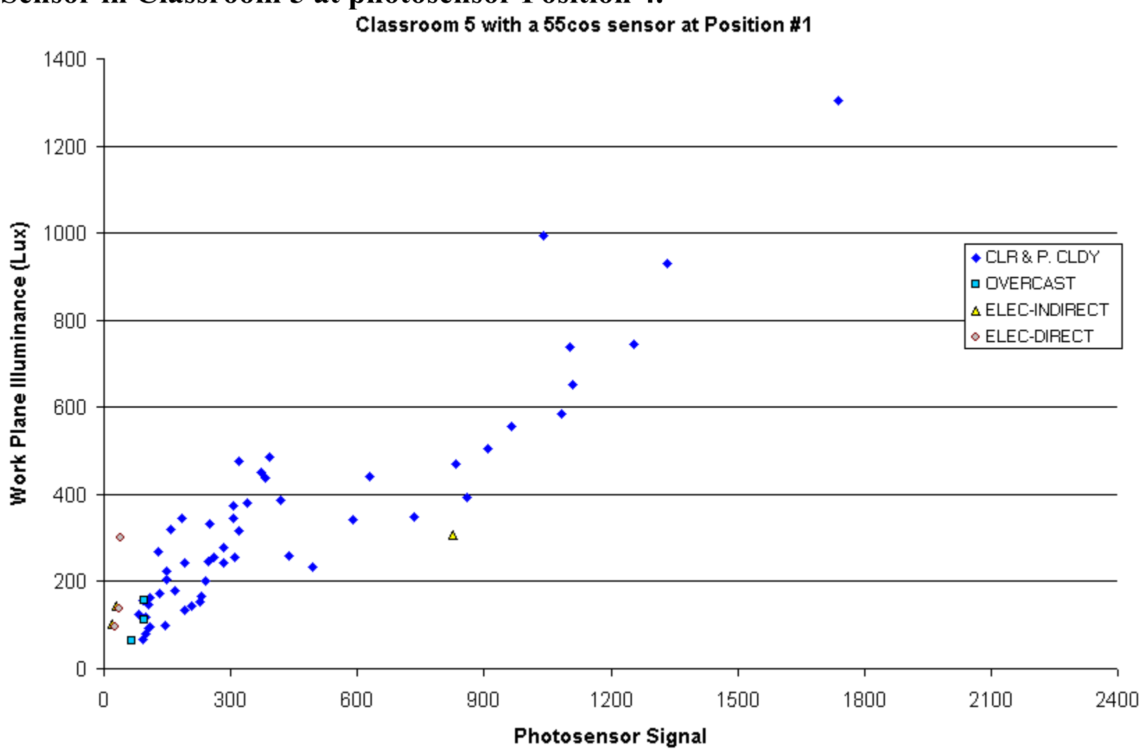


Figure 26. Graph of workplane illuminance versus photosensor signal for the 55Cos Sensor in Classroom 5 at Photosensor Position 1.

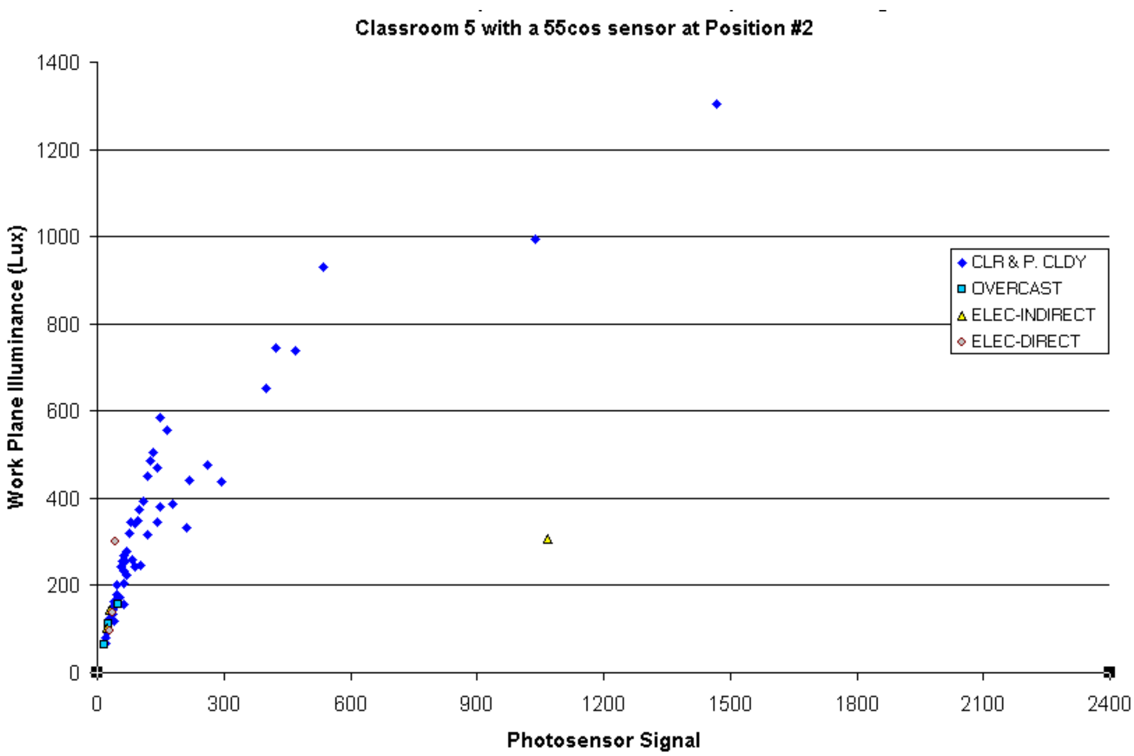


Figure 27. Graph of workplane illuminance versus photosensor signal for the 55Cos Sensor in Classroom 5 at Photosensor Position 2. All points with blinds and no direct sunlight are along the main correlation line. Only direct sunlight conditions lie to the right of the line.

The impact of sunlight patches is an important performance issue. If a teacher in a classroom allows direct sunlight to enter a space, and the photosensor is calibrated for conditions with no direct sunlight, then the system is very likely to dim the electric lighting system to a level that will provide insufficient electric light. This is because the signal provided by these daylight conditions corresponds to a signal where the amount of daylight provided on the work plane is generally much higher. For this reason, it might be beneficial for the teacher to have the ability to override the selected dimming level if more light is needed. The other option is to calibrate the photosensor under direct sunlight conditions, but this would result in the system providing significantly more electric light than needed under most other conditions, while also consuming more energy than is generally needed at a large number of times.

Figure 23 shows the relative spread in the data for the cosine sensor, with the daylight conditions that provide direct sunlight to the space clearly indicated. It is important to note that a few blind conditions that admit no direct sunlight also lie to the right of the line along which the other points are clustered. These non-sunlight conditions are for 30-degree blind angles, where the photosensor has a view of the bright ground through the tilted blinds. The solar positions at these times direct no or very little direct sunlight onto the blinds. Hence, the underside of the blinds has a relatively low luminance, while the sensor's view of the window consists of the high luminance of the sunlit ground. This is the reason why these conditions also provide a high sensor signal to work plane illuminance ratio.

When the cosine sensor is located further from the window, these conditions become more aligned with the remainder of the points. When the 55-degree half angle cosine sensor is applied at even the second closest mounting distance to the window (Figure 27), only those points that actually admit direct sunlight deviate from the trend line for the daylight conditions that do not admit direct sunlight. The summertime 30-degree blind angle conditions that have a high signal to work plane ratio occur only with the cosine sensor at the closest position to the window.

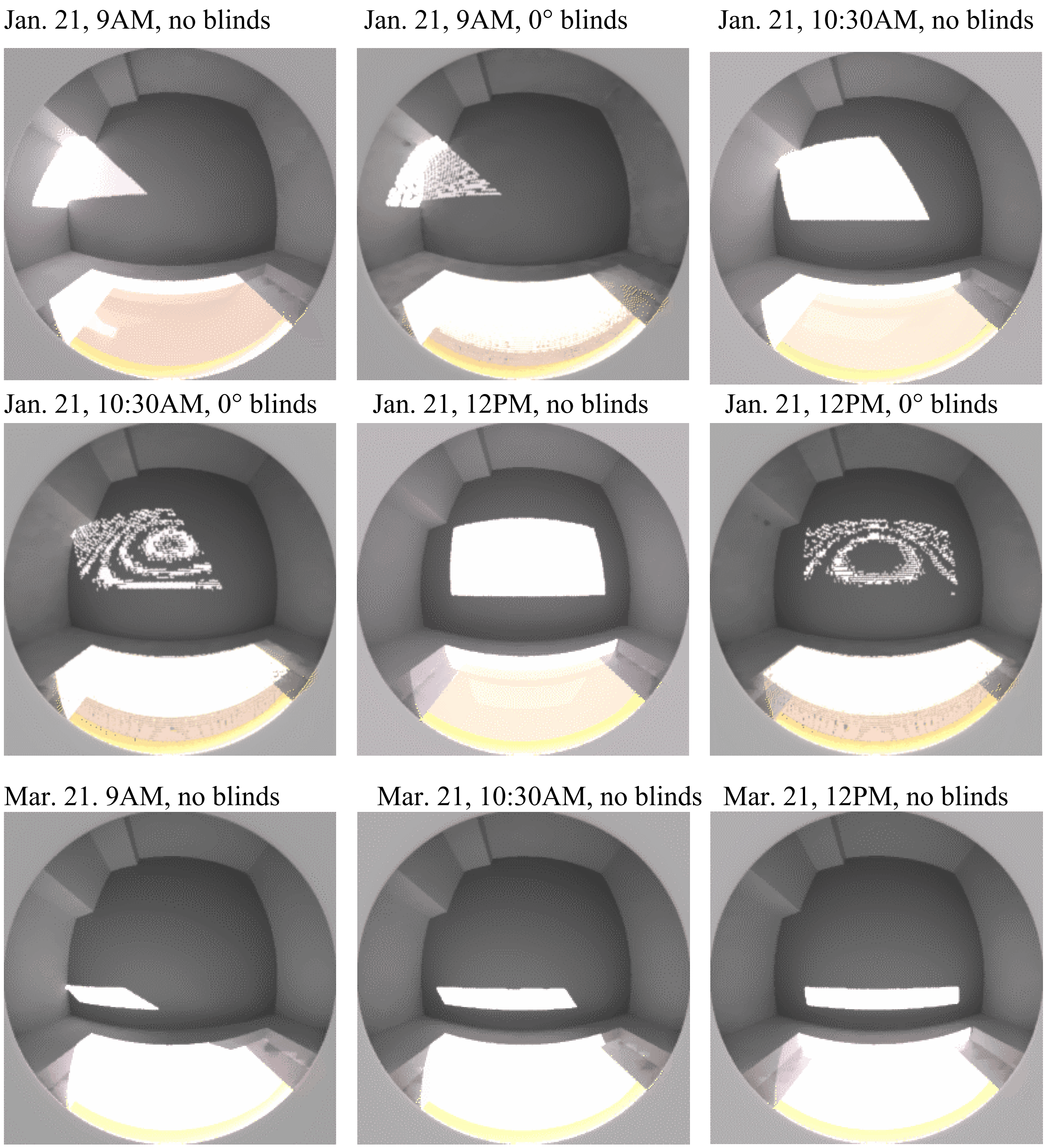


Figure 28. Example of daylight and blind conditions where direct sunlight penetrates into Classroom 5.

Impact of Indirect Lighting on Photosensor Signal

A major goal of this project is to investigate sensor spatial distribution and mounting positions. For this reason, we addressed the impact on a ceiling-mounted photosensor when pendant-mounted indirect lighting systems are present. Many photosensor systems recommend positioning the photosensor at the height of the luminaire to avoid a direct contribution to the sensor from the lighting system because the direct contribution overwhelms the photosensor. This usually involves mounting the sensor to the luminaire, which may involve additional expense. This mounting position also lowers the position of the photosensor, which restricts the photosensor's effective field of view and increases its susceptibility to be influenced by localized changes in surface reflectance (such as on a desktop).

To study the impact of indirect lighting on photosensor performance, a separate analysis was performed that addressed the photosensor mounting position between two adjacent rows of indirect luminaires. A photosensor was placed on the ceiling and moved between two rows of pendant-mounted indirect luminaires. A single luminaire type was considered with continuous rows of luminaire spaced ten feet apart and suspended two feet from the ceiling. The sensor was moved in one-foot increments between the rows of luminaires. The magnitude of the signal at different sensor positions between these two rows of luminaires is shown in Figure 29 for the various photosensors tested. Figure 30 illustrates the same data, but is graphed in relative terms, where the photosensor's signal when placed directly above a row of luminaires is assigned a value of 1.0. This graph shows the relative difference in the magnitude of the signal that can occur at these different positions. The cosine sensor signal at the midpoint is much higher than the signal for the sensors with a cutoff angle that eliminates the contribution from the luminaires.

In Figure 29, it is important to note the nearest distance from a row of luminaires at which the photosensor signal reaches a value that is near its minimum value. The sensors reach this point at a distance from the luminaires where the cutoff angle begins to have an effect. Depending on how a sensor is designed to operate, in particular whether or not it subtracts out the electric lighting contribution to isolate the daylight contribution, its location relative to the electric lighting equipment can be important. This study shows that an abrupt cutoff distribution appears to be beneficial for limiting the photosensor signal from an indirect lighting system. Optimally, a wide half-angle is desired (to limit the impact of surface reflectance changes below the photosensor), but its distribution must not admit light at high angles. Based on these studies, a 55-degree half-angle with sharp cutoff appears to meet these criteria reasonably well. Keep in mind that this analysis considers a 2-foot suspension length and 10-foot spacing between rows. Longer suspension lengths or smaller spacing between rows will decrease the width of the trough on these curves, or may eliminate it altogether depending on the luminaire layout and sensor distribution. If the sensor is capable of subtracting out the electric light contribution, any negative impact caused by a high electric light signal can potentially be eliminated, although there will likely be some error in the process of isolating the daylight signal.

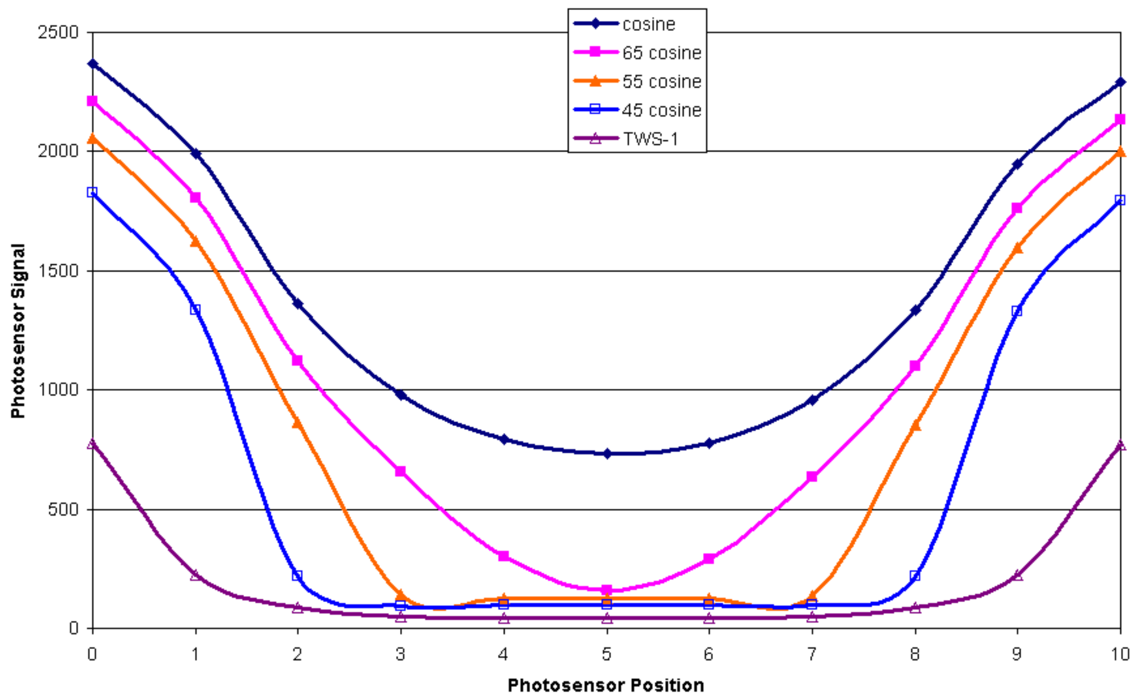


Figure 29. Photosensor signal for two rows of indirect lighting spaced 10 feet apart with luminaires suspended 2-feet from the ceiling as the photosensor moves from directly overhead row 1 to directly over row 2 in 1-foot increments.

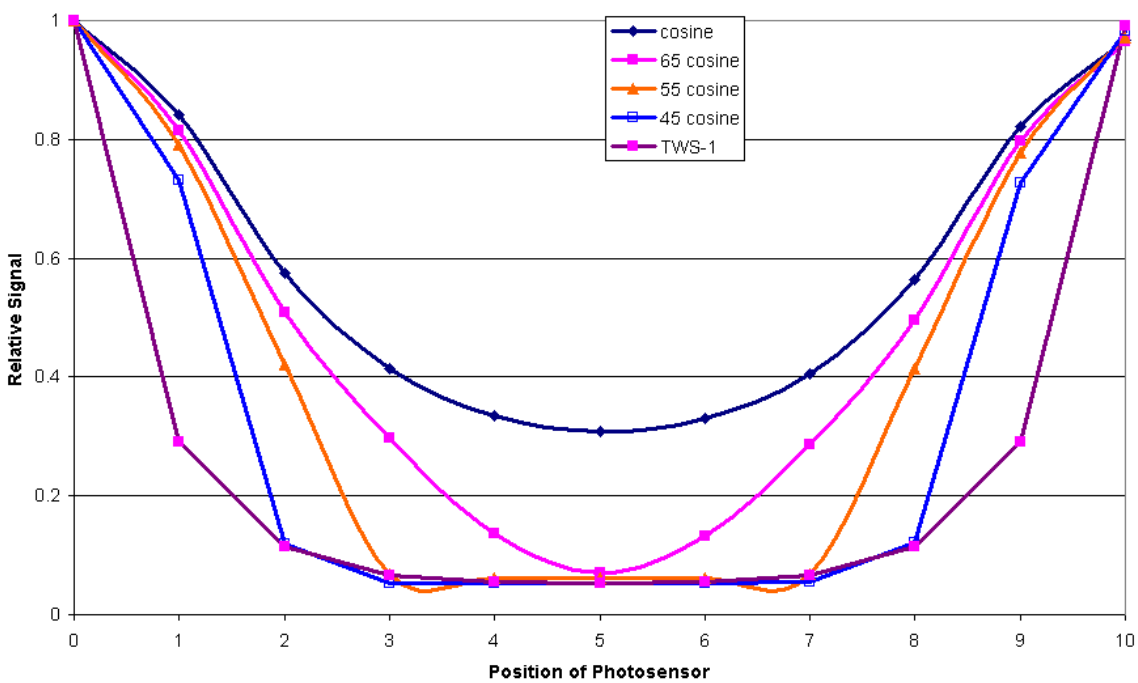


Figure 30. Relative photosensor signal for two rows of indirect lighting spaced 10 feet apart with luminaires suspended 2-feet from the ceiling as the photosensor moves from directly overhead row 1 to directly over row 2 in 1-foot increments. A value of 1.0 corresponds to that photosensor's signal when directly over a row of luminaires.

Impact Of Changes In Work Plane Reflectance

We also studied the relative impact of the reflectance of a desktop on the signal received by a photosensor. This portion of the study is to investigate reports of photosensors with relatively narrow spatial distributions being influenced by reflectance changes that occur within the sensor's field of view. For this study, a sensor was placed 7.5 feet above a 3 x 5 foot desk, and the desk was placed in a room that was illuminated to approximately 50 fc using direct and indirect lighting. The percent increase in the photosensor was then recorded for a variety of photosensor distributions. The impact of an increase in desktop reflectance from 20% to 70% for each of these sensors is provided in Figure 31. This is a rather extreme reflectance change, but one that would occur if an entire desk of relatively low reflectance was covered with white paper.

Figure 32 shows images of the desktop for a set of these conditions under a direct lighting system.

The results of this study show that sensors with narrower spatial distributions experience greater deviations in sensor signal for the same illuminance condition as the desktop reflectance is changed from 20% to 70%. The sensor signal is also more sensitive to these changes when the sensor is positioned directly over the desk. The sensor locations at the edge of the desk and beyond suggest that sensor placement relative to a surface that may experience reflectance changes can be important. Keep in mind that locating a sensor away from a desk will not completely eliminate opportunities for this type of impact to occur. One or more individuals with light colored clothing can potentially impact the signal received by a sensor if they are standing directly beneath a sensor.

From this analysis, we see that it is important to calibrate any sensor system with the furniture located within the space, unless the sensor is design to periodically recalibrate itself under conditions where daylight is absent. A conservative calibration would also locate some high reflectance material on the desk. In an elementary school classroom, room conditions may change frequently, causing changes in surface reflectances. Changes in reflectance can have an appreciable impact on the signal received by a photosensor.

Figure 31. Percent change in the photosensor signal as the reflectance of a 3 x 5 ft. desk changes from 20% to 70%.

		Photosensor Distribution				
Lighting System	**Photosensor Position**	**COSINE**	**65-COSINE**	**55-COSINE**	**45-COSINE**	**TWS-201**
Indirect	**Center of Desk**	4.8	22.6	28.2	36.4	56.5
	Edge of Desk	4.0	19.3	23.9	31.3	35.4
	2 ft. off Desk	3.1	13.2	16.2	21.7	11.1
Direct	**Center of Desk**	19.1	22.6	27.5	35.1	83.5
	Edge of Desk	17.9	21.0	25.0	31.8	53.3
	2 ft. off Desk	12.1	14.4	17.2	22.3	17.0

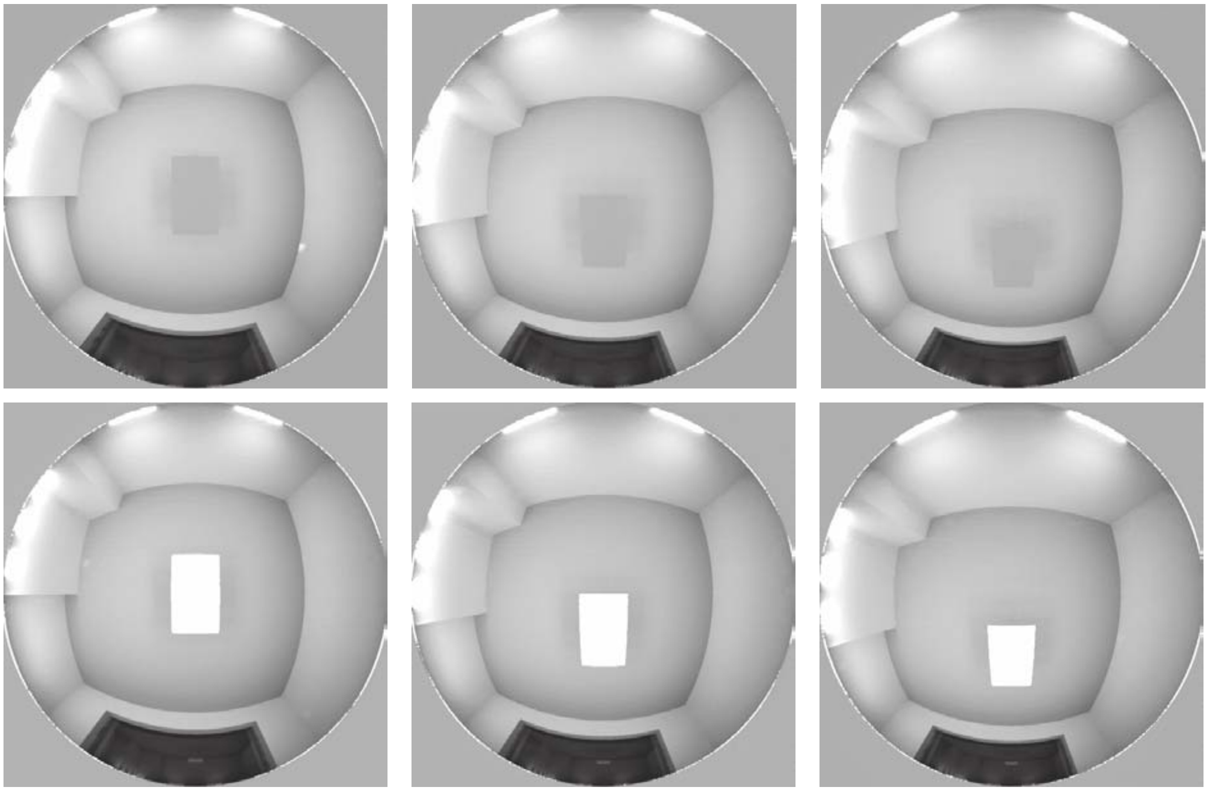


Figure 31. Photosensor fish-eye view of a desk with 20% (top) and 70% reflectance (bottom) for three photosensor locations – over the center of the desk, over the edge of the desk, and 2 feet from the edge of the desk.

Energy Analysis

An estimate of the energy that might be consumed by a photosensor-controlled dimming system was computed for each of the six classroom spaces. This study considered the energy that would be consumed over a typical year using San Francisco (airport) and Los Angeles (city) weather data. The Los Angeles weather was applied to the calculated daylight conditions, which are actually for a San Francisco site latitude, however, the differences in daylight performance at a Los Angeles latitude would not be great. Three different control zones were considered in most of the spaces, with one row, two rows and three rows of luminaires being assigned to the dimmed lighting zone for different energy study conditions. Classroom 1 and 6 were analyzed only with all of the luminaires controlled as a single zone.

The results of these energy analyses, which apply a blind condition to eliminate direct sunlight from the space when required, consider the total energy required to maintain a target illuminance level at all points along a row or column through the center of the space. The energy needed to operate the lighting system from 8:15AM until 3:45PM Standard time was determined using the time conditions that were analyzed for the graphical analysis of photosensor performance (9:00, 10:30 and 12 noon solar time). Each time was used to approximate the energy performance over a 1.5 hour interval, with the 9AM and 10:30AM times used to mirror afternoon conditions. 9AM was assumed to be a mirror image of 3PM and 10:30AM was assumed to be a mirror image of a

1:30PM daylight condition. The clear, partly cloudy and overcast sky conditions were assigned in proportion to the number of clear, partly cloudy and overcast days provided in average weather data for each month of the year at these two sites. The January 21 conditions were assumed to be similar to the conditions from December 21 through February 21, since this day is roughly an average condition across this time period. It also mirrors the conditions between October 21 and December 21. Likewise, March 21 was used for February 21 through April 21 and August 21 through October 21, while May 21 data were applied to all days between April 21 and August 21.

This analysis described above provides a general but reasonably accurate estimate of the amount of energy required to maintain the work plane target illuminance. This analysis considered only a single dimmed lighting zone, and all luminaires in this dimmed zone are dimmed to the same level. The non-uniformity presented by some of these daylight delivery systems may create a slight overestimation or underestimation of these energy values.

The different photosensor distributions, their ceiling locations, and their individual performance of these sensors at each of the tested sky conditions were not considered in this analysis. Past studies have shown that different sensors are likely to provide relatively similar results in terms of energy once they are commissioned and operated, but will differ in terms of daylight tracking ability. Daylight tracking ability is covered in the photosensor performance portion of this report. Also, this analysis only looks at the amount of electric light required given the distribution of daylight and electric light on the workplane. It is important to note that optimization of the daylight delivery systems and the lighting quality provided by these systems was not performed in this study since real space configurations were applied. Care should be taken in all classroom cases with dimmed lighting to maintain proper illuminance on the chalkboard/whiteboard, and at any other special task areas, which may require a separate lighting system.

For the energy studies, a two lamp electronic dimming ballast was assumed, considering an 88% ballast factor at full light output and 66 input watts, and achieving 5% minimum light output at 16 input watts. The dimming curve was assumed to be linear between these two points.

The results of the energy analyses are shown in Figures 32 and 33.

The energy analysis shows that for unilateral sidelighting (Classrooms 3 and 5), the lowest level of energy consumption will be achieved if the first and second rows of luminaires are dimmed. The light shelf system (Classroom 3) provided much more energy use and relatively similar total energy consumption for one row and two row dimming, indicating that a single dimmed row would be more appropriate in this design. This is likely due to the design employed and should not be generalized across all light shelf systems.

The results for systems with two daylight delivery systems that provide a bilateral daylighting approach (classrooms 2 and 4), provide minimum energy use when all three rows of luminaires are dimmed. Still, a more complete cost analysis may be necessary to determine if these designs provide a cost effective approach, since the additional savings provided by dimming a third row must be weighed against the costs of the additional dimming hardware, namely the ballasts.

Figure 32. Estimate of percent of total room lighting energy used under San Francisco average sky conditions and 12-month daily operation over the time period 8:15AM to 3:45PM.

Classroom	Luminaire	3 rows	2 rows	1 row
1	Troffer	36*	-	-
2	Troffer	42	53	73
	Pendant	51	59	73
3	Troffer	87	85	84
	Pendant	92	83	80
4	Troffer	53	61	74
5	Troffer	64	54	73
	Pendant	63	59	74
6	Troffer	45*	-	-

* All luminaires in Classrooms 1 and 6 were considered as the dimmed lighting zone.

Figure 33. Estimate of percent of total room lighting energy used under Los Angeles (City) average sky conditions and 12-month daily operation over the time period 8:15AM to 3:45PM.

		Number of dimmed rows of luminaires		
Classroom	**Luminaire**	**3 rows**	**2 rows**	**1 row**
1	Troffer	34*	-	-
2	Troffer	42	54	74
	Pendant	51	60	74
3	Troffer	87	84	85
	Pendant	92	82	81
4	Troffer	51	61	75
5	Troffer	64	53	74
	Pendant	62	59	75
6	Troffer	44*	-	-

* All luminaires in Classrooms 1 and 6 were considered as the dimmed lighting zone.

The two classrooms with skylights (classrooms 1 and 6) provide the most opportunity for reducing lighting energy due to the higher quantities of daylight provided by these systems. Due to the interior daylight coverage provided by these systems (they illuminate the entire room with daylight), they were only considered with all rows of luminaires being dimmed together. Skylights, however, may increase space cooling loads due to increased heat gain and it is critical to also evaluate heating and cooling loads to fully assess their overall impact on building energy consumption. Classroom 6 presents some rather complex conditions with three different daylight delivery paths that may necessitate further fine-tuning of the control zone.

In the case of a single row being assigned to the dimmed lighting zone, most of the daylight conditions tested permit this row of luminaires to be set at minimum light output for the period from 8:15AM through 3:45PM under all sky conditions tested. This is evident in the results for Classrooms 2, 4 and 5 when one row is dimmed and the energy values are very near the 74%

value that we could theoretically achieve if the dimming level of this single row was fixed at its minimum setting across this time period. Note that turning this row off entirely at all times would result in energy consumption that is 66.7% of the level when all three rows are operating. No shutoff feature was incorporated into this study; therefore the minimum achievable value when one row is dimmed is 74% of the total room energy. The theoretical minimum value is 47.5% when two rows are dimmed to 5% light output at all times and 21.2% when all three rows are dimmed to this level.

Another control option to analyze would be a photosensor control system that permits both the first and second row of luminaires to be dimmed at different levels. At a relatively low daylight level that does not require the perimeter row to be set to minimum, this approach would achieve an additional reduction in lighting power required that is approximately 8% of the entire room power in Classroom 8. This analysis considered that as the perimeter row is dimmed to a lower value, the second row must be set higher than it would be if coupled with the first row to maintain the target illuminance at the critical point (the critical point is the point most likely to drop below the target illuminance level). At higher daylight conditions, where two rows of luminaires might already be set to a minimum value, the savings achieved by dimming the two rows to different levels would vanish. Over the course of the year, a rough estimate is that perhaps the energy consumption can be reduced an additional 3-6% of the total room energy with this more advanced configuration. This arrangement would be significantly more complex to design and calibrate/commission, particular in classrooms with more complex daylight delivery systems.

Summary

This detailed study of photosensor performance has provided important information regarding photosensor performance in a classroom space under a variety of different daylight conditions. This study has involved an analysis of the following impacts on photosensor performance:

1. Photosensor spatial sensitivity
2. Photosensor location
3. Impact of direct vs. indirect lighting
4. Impact of changes in reflectance on the work plane.
5. Location of the critical point, which is the point used for the calibration of system performance.
6. Dimmed lighting zone configuration (number of rows of luminaires applied to dimmed zone).

The following are general conclusions that have been derived from the data gathered in this study.

1. Photosensors that receive a significant amount of light from the windows do not have as high a correlation between the photosensor signal and the work plane illuminance as does a photosensor whose signal from a daylight aperture is small. This holds for narrow sensors and for wide sensors that are located away from a window.
2. A photosensor location that reduced the photosensor's view of the window is desirable. However, placing the photosensor too deep into a room will result in a low daylight

signal and therefore a steep daylight signal to work plane illuminance correlation line, which would make the system more difficult to calibrate. The daylight signal may also drop below the electric light signal, which could create control problems.

3. Points that permit direct sunlight to enter a space appear to deviate from most of the other points on a work plane illuminance to photosensor signal graph in most situations. For these conditions, the higher photosensor signal would generally result in the system providing a dimming setting that is too low.
4. The dimmed electric lighting system can produce a signal with a lower slope that the slope for the daylight correlation line when a photosensor receives too much light from an indirect lighting system.
5. A cutoff angle of 55 degree appears to work reasonably well at minimizing the signal received from an indirect lighting system, but should not be mounted within 3 feet of a luminaire than is suspended 2 feet from the ceiling.
6. A wider photosensor spatial distribution is impacted less by changes in room surfaces reflectances. In addition, mounting the sensor away from any surfaces, such as a desktop, can help to reduce the impact of desktop reflectance.
7. The critical point for a classroom that consists of three rows of luminaires (direct or indirect), and where the outside two rows of luminaires make up the dimmed zone controlled by the photosensor, is generally located within one to two feet of the center row of luminaires, and for simplicity, can be located directly beneath that second luminaire row. Also, locating this point closer to the side wall than the center of room, on the side of the room that receives less daylight for the daylight condition provided at the time of calibration should be the most appropriate location.
8. A dimmed lighting zone can generally consist of the first two rows of luminaires from the window in an unobstructed classroom space when the daylight condition involves only sidelighting. Energy savings for the space are likely to be in the range of 30-45% with a sidelighting condition that provides generous levels of daylight, even with the application of horizontal blinds.
9. Dimming of a single row of luminaires (along a window wall) will allow that row of luminaires to be placed at the minimum light output setting a large fraction of the year in a space with ample daylight.
10. In spaces with toplighting or bilateral daylighting, it may be possible to dim all of the luminaires in the space. Whether or not this is possible depends on the uniformity of the daylight under a range of sky conditions.

To summarize the above results, a wide sensor, such as a cosine sensor is likely to provide less than optimum results due to its tendency to respond to light from both windows and indirect luminaires. A wide sensor with sharp cutoff, such as one with about a 55-degree half angle, appears to perform quite well, with respect to limiting the direct response from windows and from an indirect lighting system, while also receiving flux from a broad area to minimize the effects due to changes in reflectance across the work plane.

It is important to note that certain characteristics that can be added to the photosensor system's control algorithm can reduce some of the negative impacts that are experienced in ceiling-mounted photosensor systems. For example, the system may subtract out the system that results from the dimmed portion of the electric lighting system based on the dimming system signal that it is providing. This estimate of the signal can also potentially be updated to account for changes in reflectance and light loss factors that occur over time.

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